12-2007

Load Shedding Algorithm Using Voltage and Frequency Data

Poonam Joshi
Clemson University, poonsjosh@gmail.com

LOAD SHEDDING ALGORITHM USING VOLTAGE AND FREQUENCY DATA

A Thesis
Presented to
The Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Electrical Engineering

by
Poonam M. Joshi
December 2007

Accepted by:
Dr. Adly Girgis, Committee Chair
Dr. Elham Makram
Dr. John Gowdy

ABSTRACT

Under frequency load shedding schemes have been widely used, to restore power system stability post major disturbances. However, the analysis of recent blackouts suggests that voltage collapse and voltage-related problems are also important concerns in maintaining system stability. For this reason, both frequency and voltage need to be taken into account in load shedding schemes. The research undertaken here considers both parameters in designing a load shedding scheme to determine the amount of load to be shed and its appropriate location. An introduction about the need for a load shedding scheme and the purpose of doing research on this particular topic is given. This is followed by a discussion on the literature review of some of these schemes. The discussion is divided into two parts. The first part is about the actual load shedding schemes used in the power industry world wide. The second part gives a detailed overview about the two types of load shedding schemes, namely the under frequency and under voltage load shedding schemes.

The methodology used for the proposed load shedding algorithm includes frequency and voltage as the inputs. The disturbance magnitude is estimated using the rate of change of frequency and the location and the amount of load to be shed from each bus is decided using the voltage sensitivities. The methodology describes the algorithm in a stepwise manner and gives brief information about the test system and the PSS/E software used to model the disturbance. The test systems used are the IEEE 39 bus system and IEEE 50 bus system. The disturbances modelled are the loss of a generator for various buses and the loss of transmission lines for various cases. The observations

and results obtained from the simulations comprise of the frequency and voltage plots before and after applying the proposed load shedding scheme. The load shedding scheme is implemented on an equivalent system provided by Duke Energy. The data has been collected from a Duke simulator. The calculations for determining the magnitude of the disturbance and the amount of load shed from each bus are also presented here. The conclusion chapter includes the summary of the observations and suggestions for future work.

ACKNOWLEDGEMENT

I would like to thank my advisor Dr. Adly Girgis for his guidance and support throughout my graduate level education. I would also like to express my sincere thanks to my other committee members, Dr. Elham Makram and Dr. John Gowdy for their valuable suggestions.

TABLE OF CONTENTS

Page

TITLE PAGE ………………...i

ABSTRACT……………………………………………………………………………….ii

ACKNOWLEDGEMENTS………………………………………………………………iv

LIST OF TABLES……………………………………………………………………….vii

LIST OF FIGURES……………………………………………………………………..viii

CHAPTER

1. INTRODUCTION……………………..………………………….........................1

    Conventional Load Shedding schemes in the industry……………………….....2

    Problem Statement………………………………………………………………...4

2. LOAD SHEDDING TECHNIQUES……………………………..….........................6

    Industry techniques for load shedding around the world……….........................6

    Research on Under frequency load shedding schemes………………………..12

    Research on Under voltage load shedding schemes...…………………...........22

3. PROPOSED LOAD SHEDDING SCHEME……………………………...……..29

    Methodology for the proposed load shedding scheme ……………………….29

    Test system modeling in PSS/E………………………………………………….40

Table of Contents (Continued)

Page

4. OBSERVATIONS ON THE IEEE TEST SYSTEMS…………………………43

Case study 1: Loss of a generator for the IEEE 39 bus system ..……………..43

Test cases for IEEE 39 bus system: Loss of a generator…...……...................49

Case Study 2: Loss of a generator for IEEE 145 bus system…………………54

Case Study 3: Loss of a transmission line…………………………………….61

Duke Energy System : Loss of a generator…………………………...........65

5. CONCLUSIONS AND FUTURE WORK………………….…..….......................72

Conclusions……………………...…….……………………………………72

Future Work…….…………..……….……………………………………...74

APPENDICIES…………………………………………………...............……….77

A: Code for the Load Shedding Scheme……..……..………………………….78

B: IEEE System Data…………………………………………..…………79

REFERENCES…………………..…………………….....………………………………..82

LIST OF TABLES

Table Page

2.1 FRCC Load shedding steps……………………………………….................8

2.2 MAAC Load shedding steps…………………………………......................9

2.3 ERCOT system load shedding steps…………………………………….…...12

2.4 SCADA based load shedding data………………..……………......................22

2.5 Load Shed By the Hellenic Transmission System Operator....…………………....28

4.1 Voltage sensitivities at each load bus for IEEE 39 bus system (Case Study 1)…………………….……………......................................50

4.2 Load shed at each bus for IEEE 39 bus system (Case Study 1).........................51

4.3 IEEE 39 bus system disturbance test cases ………........……………………54

4.4 Load shed at each bus for each test case of the IEEE 39 bus systems……………..……………………………………………………...........55

4.5 MW generation lost for loss of a generator (IEEE 145 bus system)…………...59

4.6 Load shed at each bus for test cases 1-5 (IEEE 145 bus system)……………....60

4.7 Load shed at each bus for test cases 6-10 (IEEE 145 bus system)……….....…61

4.8 MW generation lost due to a transmission line loss…….…………………...66

4.9 Load shed at each bus for the Duke Energy System…….………………….71

4.10 Load shed at each bus for the Duke Energy System (contd)…………………..72

LIST OF FIGURES

Figure Page

2.1 Block Diagram of the ILS scheme……………………………….…....................15

4.1 Instantaneous rate of change of frequency plot…………………………….........33

4.2 Average rate of change of frequency…………………………………….........34

4.3 Q-V analysis graph (Q Mvar versus V p.u)……………………………………….39

4.4 Load Shedding Algorithm…………………………………………………….…...42

4.5 IEEE 39 bus system…………………………………………….………….……...44

4.6 IEEE 39 bus system : Average System Frequency (without load shedding)...........48

4.7 IEEE 39 bus system : Voltage at bus 7 without load shedding..……........……...49

4.8 IEEE 39 bus system : Case study 1 Frequency (applying Load shedding)..……...52

4.9 IEEE 39 bus system : Voltages at buses 7,8 and 31 after load shedding …...........53

4.10 IEEE 39 bus system unacceptable case: Voltage at bus 7 when generator 34 is lost (before and after applying load shedding)…….……………………...…56

4.11 IEEE 39 bus system acceptable case: Frequency when generator 34 is lost (without load shedding)……….……………………………………………...57

4.12 IEEE 39 bus system acceptable case : Frequency when generator 34 is lost (applying load shedding)…………………….……………………………….…….58

4.12 IEEE 39 bus system acceptable case : Voltage at bus 7 when generator 34 is lost (before and after load shedding)……………………...………...……...…58

List of figures (continued)

Figure Page

4.13 IEEE 145 bus system unacceptable case: Voltage at bus 7 (before and after applying load shedding)……………………..…………………….………........63

4.14 IEEE 145 bus system unacceptable case : Frequency with load shedding.……….63

4.15 IEEE 145 bus system acceptable case : Voltage at bus 7 (with load shedding)………..……………………………………………………………...64

4.16 IEEE 145 bus system acceptable case : Frequency with load shedding ………….65

4.17 IEEE 39 bus system : Voltage at bus 7 due to the tripping of line 16-19 (without load shedding)……………………….………….…………………67

4.18 IEEE 39 bus system : Frequency due to the tripping of line 16-19 (without load shedding)..…………………………………………………….….….68

4.19 IEEE 39 bus system : Frequency plot after tripping line 16-19 (applying load shedding)……………………………..……………………….................69

4.20 Frequency of the Duke Energy System with and without load shedding..……….72

4.21 Voltage profile at Allen (duke energy system bus) with and without load shedding……………………………………..……………......................73

4.22 Voltage profile at Catawba (duke energy system bus) with and without load shedding……………………..……………………………………...................74

4.23 Voltage profile at Shiloh (duke energy system bus) with and without load shedding……………………………...…………………………….............74

4.24 Voltage profile at Marshall (duke energy system bus) with and without load shedding……………………………….…..………………………….............75

CHAPTER 1

INTRODUCTION

The developing industries and their growing infrastructure have stressed the power industry to supply sufficient power. The generation capacity should increase in proportion to the increase in the number of loads. Large power transfers across the grid lead to the operation of the transmission lines close to their limits. Additionally, generation reserves are minimal and often the reactive power is insufficient to satisfy the load demands. Due to these reasons power systems become more susceptible to disturbances and outages.

Some of the disturbances experienced by the power system are faults, loss of a generator, sudden switching of loads [1]-[3]. These disturbances vary in their intensity. At times these disturbances might cause the system to be unstable. For example, when a sudden large industrial load is switched on, the system may become unstable. As a result it is necessary to study the system and monitor it in order to prevent it from becoming unstable. The two most important parameters to monitor are the system voltage and frequency. The voltage at all the buses and the frequency, both of which must be maintained within prescribed limits set by FERC [5] standards to ensure that the system remains stable. The frequency is mainly affected by the active power, while the voltage is mainly affected by the reactive power.

Specifically, the frequency is affected by the difference between the generated power and the load demand. This difference is caused due to disturbances which reduce the generation capacity of the system. For example, due to the loss of a generator, the generation capacity decreases while the load demand remains constant. If the other generators in the system are unable to supply the power needed, then the system frequency begins to decline. To restore the frequency within the prescribed limits a load shedding scheme is applied to the system.

In addition, the reactive power demand of the load affects the voltage magnitude at that particular bus. When the power system is unable to meet the reactive power demands of the loads, the voltages become unstable. In such situations, capacitor banks are switched on to supply the reactive power to the loads. However, when these capacitor banks are unable to restore the voltage levels within their upper and lower limits, the system resorts to load shedding.

Post disturbance, the system must return to its original state, meaning the load which was shed has to be restored in a systematic manner without causing a system collapse. Because of its importance in maintaining power system stability, load shedding has become an important topic of research.

Conventional Load Shedding Schemes in Industry

Load shedding is an emergency control operation. Various load shedding schemes have been used in the industry. Most of these are based on the frequency decline in the system. By considering only one factor, namely the frequency, in these schemes the results were less accurate. Although the earlier schemes were considerably successful, they lacked efficiency. They shed excessive load which was undesirable as it caused inconvenience to the customers. Improvements on these traditional schemes led to the development of load shedding techniques based on the frequency as well as the rate of change of frequency. This led to better estimates of the load to be shed thereby improving accuracy.

Recent blackouts have brought our attention to the issues of voltage stability in the system. Voltage decline can be a result of a disturbance. Its main cause, however, is insufficient supply of reactive power. This has led researchers to focus on techniques for maintain voltage stability. The loss of a generator causes an unbalance between the generated power and the load demand. This affects the frequency and voltage. Load shedding schemes must consider both these parameters while shedding load. By shedding the correct amount of load from the appropriate buses, the voltage profile at certain buses can be improved.

After considering the parameters for load shedding, it is also necessary to have the suitable equipments for collecting system data so that the inputs for the shedding scheme are as accurate as the actual values. The measurement and recording equipments for analysis have undergone developments. Usually, phasor measurement units, PMU are used for measuring real time data.

The load shedding is on a priority basis, which means shedding less important loads, while expensive industrial loads are still in service. Thus the economic aspect plays an important part in load shedding schemes. Usually, a step wise approach is incorporated for any scheme. The total amount of load to be shed is divided in discrete steps which are shed as per the decline of frequency. For example, when the frequency decreases to the first pick up point a certain predefined percentage of the total load is shed. If there is a further decay in frequency and it reaches the second pickup point, another fixed percentage of the remaining load is shed. This process goes on further till the frequency increases above its lower limit. Increasing the number of steps reduces the transients in the systems. The amount of load to be shed in each step is an important factor for the efficiency of the scheme. By reducing the load in each step the possibility of over shedding is reduced. While considering the amount of load to be shed and the step size, it is also important to take into account the reactive power requirements of each load. Quite often, disturbances such as a generator loss cause the voltage to decline. An effective way to restore voltage is to reduce the reactive power demand. Thus when loads absorbing a high amount of reactive power are first shed; the voltage profile can be improved.

Problem statement

Despite being successful to a great extent, the conventional load shedding schemes have certain disadvantages as mentioned above. These are summarized in the following paragraph. The amount of a load step is, at times, large which causes excessive load to be shed. Most schemes do not have the flexibility to increase the number of load shedding steps, thereby introducing transients in the system. Voltage stability is not considered most of the times for load shedding as the schemes focus on monitoring frequency and its rate of change. The load shedding algorithm devised in this research has tried to overcome some of these disadvantages. It is based on two key parameters; the frequency and voltage. For considering the voltage stability, sensitivities from the QV analysis at load buses constitutes the major part of the algorithm.

A real time monitoring of the system frequency and voltage is done using real time observations from synchrophasors. The system frequency measurements are used to plot the rate of change of frequency plot of the system. Using the rate of change of frequency gives results which are much more accurate as opposed to using just the frequency data. These observations are recorded simultaneously throughout the system. Thus the voltage at all the buses at anytime can be recorded with minimum amount of error in the observations.

Thus if the voltage is falling below a certain limit, its early detection is possible. The voltage and frequency deviations can be calculated based on this detection. The frequency falling below a certain limit is an indication of the power mismatch between the generated and load power. In order to reduce or completely eliminate this power mismatch the system is resorted to load shedding which decreases the load demand, thus matching the generated power and the load demand. Also, the voltage profile of the system improves due to efficient load shedding since the voltage sensitivities are an important factor for shedding load.

CHAPTER 2

LOAD SHEDDING TECHNIQUES

Different methods for load shedding and restoration have been developed by many researchers. Currently there are various load shedding techniques used in the power industry world wide. These conventional load shedding schemes are discussed in the first sections of the following chapter. The second section includes a discussion on under frequency and under voltage load shedding techniques which are proposed by researchers and are yet to be incorporated by the power industry.

Industry Techniques for Load Shedding

Some of the conventional industry practices for load shedding are discussed in the upcoming section. The Florida Reliability Coordinating council (FRCC) [6], has definite load shedding requirements. The load serving members of FRCC must install under frequency relays which trip around 56% of the total load in case of an automatic load shedding scheme. It has nine steps for load shedding. The pickup frequencies are 59.7 Hz for the first step and 59.1 Hz for the last step. The frequency steps, time and the amount of load to be shed is in the table 1. The steps from A to F follow the shedding of load as per a downfall in the frequency. The steps L, M and n are peculiar since they indicate load shedding during a frequency rise. The purpose of this is to avoid stagnation of frequency at a value lower than the nominal. Thus if the frequency rises to 59.4 Hz and continues to remain in the vicinity for more than 10 seconds, 5% of the remaining load is shed so that the frequency increases and reaches the required nominal value.

TABLE 1: FRCC Load Shedding Steps

UFLS Step	Frequency (hertz)	Time Delay (seconds)	Amount of load to be shed (% of the total load)	Cumulative amount of load (%)
A	59.7	0.28	9	9
B	59.4	0.28	7	16
C	59.1	0.28	7	23
D	58.8	0.28	6	29
E	58.5	0.28	5	34
F	58.2	0.28	7	41
L	59.4	10	5	46
M	59.7	12	5	51
N	59.1	8	5	56

The effectiveness of this scheme is tested every five years by the FRCC Stability Working Group (SWG). Based on this scheme certain frequency targets are established. The frequency must remain above 57 Hz and should recover above 58 Hz in 12 seconds. In addition, the frequency must not exceed 61.8 Hz due to excessive load shedding.

Another scheme implemented by California ISO incorporates both automatic as well as manual load shedding [7]. There are certain guidelines to implement the automatic load shedding. If the frequency goes lower than 59.5 Hz, the status of the generators is noted. If sufficient load has not been shed further steps of load shedding are undertaken. There are instructions regarding the duties to be performed by the shift manager. Some of the standard points to be followed are stated here. The immediate action on account of a decision to shed load is to inform the market participants regarding the suspension of the hour ahead or the day ahead markets due to system disturbances. Manual load shedding is ordered in case additional load shedding is required to correct the frequency.

The Mid Atlantic Area Control, MAAC [8] undertakes a stepwise load shedding procedure. Generator protection is also considered when establishing the frequency set points and the amount of load to be shed at each step. The generator protection relay is set to trip the generators after the last load shedding step. The scheme has the following requirements. They have three basic load shedding steps as shown in table 2.

TABLE 2: MAAC Load Shedding Steps

Amount of load to be shed (percentage of total load)	Frequency set points (Hertz)
10%	59.3
10%	58.9
10%	58.5

The first pickup frequency is 59.3 Hz as can be seen. At each step 10% of the online load at that instant is shed. The number of load shedding steps can increase to be more than three provided the above schedule is maintained. This scheme is a distributed scheme as it sheds loads from distributed locations as opposed to centralized schemes. The loads tripped by this scheme are manually restored.

Time delay settings are applied to the under frequency relays with a delay of 0.1 seconds. These relays are required to maintain a + or -0.2 Hz stability in set point and + or -0.1 seconds in time delay. The styles and manufacturing of these relays is required to be identical to obtain approximately similar response rates. An Under frequency load shedding database maintained by the MAAC staff stores information regarding the load shed at each step, the total number of steps and records every load shedding event.

The Public Service Company of New Mexico (PNM) has developed an under voltage load shedding scheme [9] to protect their system against fast and slow voltage instability. The scheme has been designed for two voltage instability scenarios. The first one is associated with the transient instability of the induction motors within the first 0-20 seconds. The second one is up to several minutes. This collapse may be caused due to the distribution regulators trying to restore voltages at the unit substation loads. According to the topology of the PNM system the Imported Contingency Load Shedding Scheme has been developed (ICLSS). This scheme uses distribution SCADA computers and consists of PLCs. The Albuquerque area system has been used for testing this method. Thirteen load shedding steps were required to correct the frequency deviation.

The South West Power Pool, SPP, has the basic three step load shedding scheme based on under frequency relays [10]. In case the frequency decline cannot be curbed in three steps, additional shedding steps are carried out. Other actions may include opening lines, creating islands. These actions are carried out once the frequency drops below 58.7 Hz. The scheme is inherently automatic but in case it fails to achieve successful frequency restoration, manual load shedding is incorporated. As stated before, the members are required to shed loads in three steps. In the first step, up to 10% of the load but no more than 15% is required to be shed. In the second step up to 20% of the load but no more than 25% is required to be shed. The third step requires up to 30% but not more than 45% of the existing load to be shed.

Besides the load shedding scheme in the US, there have also been certain techniques in other power systems of the world. Malaysia's TNB system [11] has been using one such scheme. This scheme is based on the decline of frequency and sheds load as the frequency decreases below its nominal value. It was initially a four step load shedding scheme. But after a system collapse in August 1993, it was revised to a six step scheme shedding. Since this is a 50 Hz system, the shedding begins from 49.5 Hz. The consecutive frequencies for the next five steps are 49.3 Hz, 49.1 Hz, 49.0 Hz, 48.8 Hz and 48.5 Hz. The proportion of the load selected for shedding is based on the average of three months of load data and is annually updated. The first three steps of load shedding are set up at three manned substation or substations with remote supervisory control. The amount of load seems to be lesser when the load to be shed is evenly distributed over the system. A new eleven step scheme has been recently suggested.

An automatic under frequency load shedding scheme is used by the Guam power industry [12]. It tries to minimize the load to be shed based on the severity of load unbalance and the availability of spinning reserves. It is based on the declining average system frequency. A similar scheme is incorporated between Cote d'Ivoire-Ghana-Togo-Benin [13]. It has established a five stage load shedding scheme with the first pick up frequency of 49.5 Hz (on a 50 Hz system) and the pick up frequency of the last stage is 47.7 Hz.

ERCOT, Electric Reliability Council of Texas, has an efficient under frequency load shedding scheme [14]. It is reviewed by the ERCOT Operating guides every five years. The total load it sheds is up to 25% of the system load. Similar to the basic under frequency scheme it constitutes of three steps. It's pickup frequency for step one is 59.3 Hz as shown in table 3.

TABLE 3: ERCOT System Load Shedding Scheme

Frequency Threshold	Load Relief
59.3 Hz	5% of the ERCOT System Load (Total 5%)
58.9 Hz	An additional 10% of the ERCOT System Load (Total 15%)
58.5 Hz	An additional 10% of the ERCOT System Load (Total 25%)

The above scheme does not include any planned islanding. The only contingency considered is the loss of a generator. In an event of May 2003 the UFLS program was actually put to test. It worked fine by tripping loads uniformly. Up to 3900 MW of generation was tripped. But it was observed that some of these units tripped after the initial event and shedding of the UFLS load. These units were found to have incorrect protective relay or control settings.

An intelligent adaptive load shedding scheme proposed by Haibo You et al [15] divides the system into small islands when a catastrophic disturbance strikes it. Further, an adaptive load shedding scheme is applied to it based on the rate of change of frequency decline.

Another scheme [16] uses the artificial neural networks to determine the most appropriate load shedding protection scheme. The inputs to the system are the desired probabilistic criteria concerning the system security or the amount of customer load interruptions. This scheme is an extended version of an existing sequential Monte Carlo simulation approach.

An under frequency load shedding scheme incorporated by the Taiwan power system [17] considers various load models, for example, a single motor dynamic model, a two motor dynamic model and a composite dynamic model. This scheme calculates the dynamic D-factors, which are the coefficients of various load models depending on load frequency and voltage. A genetic algorithm load shedding scheme, called the Iterative Deepening Genetic Algorithm (IDGA) [18] sheds appropriate load at each sampling interval and minimizes the total losses of the system due to unnecessary load shedding.

An Intelligent Load Shedding scheme [19] is introduced by Shokooh et al. This scheme has been installed at PT Newmont Batu Hijau, a mining plant in Indonesia. This scheme is computerized with a main server linked to PLCs distributed throughout the system. These PLCs notify the ILS server in case of disturbances anywhere in the system.

Another method applied to the Northern Chilean system for testing purposes [20], considers optimizing the economic dispatch problem, fast spinning reserves and load shedding when a generator loss occurs in the system. This scheme uses the Bender's Decomposition Algorithm. It also considers the cost analysis of the system considering the load shedding cost and the spinning reserve cost. Most of the schemes used for Load shedding use two methods. Under frequency load shedding and under voltage load shedding.

Under Frequency Load Shedding Schemes

Under frequency load shedding mainly sets up relays to detect frequency changes in the system. As soon as the frequency drops below a certain value a certain amount of load drops, if the frequency drops further, again a certain amount of load is dropped. This goes on for a couple of steps. The amount of load to be shed and the location of the load to be shed is predetermined. The following are the summaries of certain research papers based on under frequency load shedding.

Terzia [21] talks about under frequency load shedding in two stages. During the first stage the frequency and rate of frequency changes of the system are estimated by non-recursive Newton-type algorithm. In the second algorithm, the magnitude of the disturbance is estimated using the simple generator swing equation.

In another approach Thalassinakis et al [22] have obtained results from an autonomous power system on the Greek Islands of Crete and the results are discussed in the paper. The method uses the Monte Carlo simulation approach for the settings of load shedding under frequency relays and selection of appropriate spinning reserve for an autonomous power system.

The settings of the under frequency relays are based on the four parameters; the under frequency level, rate of change of frequency, the time delay and the amount of load to be shed. Three sets of system indices are defined. These sets are for the purpose of comparisons between load shedding strategies. A method was developed which simulated the behavior of a power system. The three aspects of the power systems that were developed in the simulation were

- Operation of the power system as performed by the control centre.
- Primary regulation of the generating units after the failure of a generating unit.
- Secondary regulation and utilization of the spinning reserves.

Three different cases of comparing the spinning reserves with the load mismatch are considered. One, when the spinning reserve is sufficient or greater. Thus the load can be restored immediately. Second, when the spinning reserve is slightly insufficient and the rapid generating units will require a certain amount of time to be started. Thus it will be 10-20 minutes before the load can be completely restored. Third, the spinning reserves are insufficient and there are not enough rapid generating units thus implying that the load will not be restored for a considerably long period of time.

Another method [23] triggers the under frequency relays based on a dynamically changing intelligent load shedding scheme. The main components of this scheme are the knowledge base, disturbance list and the ILS computation engine.

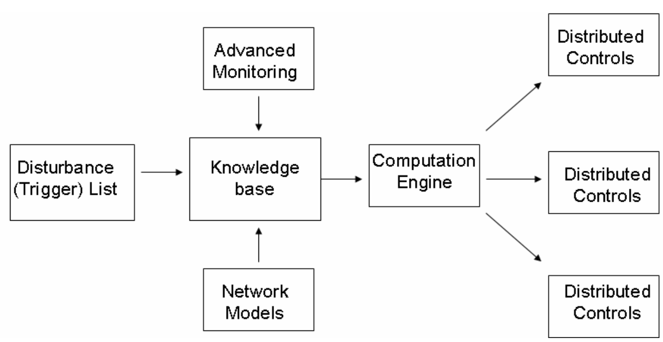

Fig. 1 Block Diagram of the ILS scheme

The generalized structure of the ILS scheme is shown in figure 1. The knowledge base is the most important block. It is connected to the computation engine which sends trip signals to relays. The network models can be accessed by the knowledge base while monitoring the system.

The knowledge base is trained and its output consists of system dynamic scenarios and frequency responses during disturbances. This trained knowledge base also monitors the system continuously for all operating conditions. The disturbance list consists of pre-specified system disturbances. Based on the inputs for the system and the continuous system updates, the knowledge base notifies the ILS engine to update its load shedding list. Thus it ensures that the load shed is always minimum and optimum.

Wee-Jen Lee [24] discuss about another intelligent load shedding based on micro-computers. The unique feature about this relay is the built in frequency setting and the time delay setting.

The frequency setting in the relay counters system re collapse situation. An example of system re collapse is as follows. Consider a generator loss which triggers a load shedding step. This causes the frequency of the system to recover. During this recovery period if another generator trips it results in a system re collapse. Typical frequency relays will not trip until the second generator loss causes sufficient frequency decay. The ILS system automatically adjusts the frequency settings such that load is shed immediately without delay.

The time delay settings cause the load scheme to initiate during situations when a disturbance causes the frequency to drop and hold at a value less than the rated. The number of load shedding steps can be increased without a limit. The advantage of having large number of load shedding steps is that it prevents large amount of transients. It also prevents over shedding.

Denis Lee Hau Aik, [25] suggests a method using the System Frequency Response SFR and the Under Frequency Load Shedding UFLS together to get a closed form expression of the system frequency such that the UFLS effect can be included in it. On doing this, the system and UFLS performance indicators can be calculated. Thus these indicators can be used efficiently in any further optimization techniques of SFR – UFLS model.

One such method has been discussed using the regression tree by Chang et al [26]. The regression tree is utilized to interpolate between recorded data to give an estimate of the frequency decline after a generator outage. It is a non parametric method which can select the system parameters and their relations which are most relevant to the load imbalance (due to generator outage) and the frequency decline. The case considered here is only a generator outage but this method can be applied to other forms of disturbances as well.

A Kalman filtering-based technique by A.A. Girgis et al [27] estimates frequency and its rate of change which is beneficial for load shedding. The noisy voltage measurements are used to estimate the frequency and its rate of change. A three-state extended Kalman filter in series with a linear Kalman filter is used in a two stage load shedding algorithm. The output of the three stage Kalman filter acts as the input to the linear Kalman filter. It is the second filter which identifies linear components of the frequency and its rate of change. The amount of load to be shed is calculated using the linear component of the estimated frequency deviation.

Another method uses Kalman filtering [28] to estimate the frequency and its rate of change from voltage waveforms. The buses are ranked based on their rate of change of voltage (dV/dt) values. The disturbance magnitude is calculated from the swing equation. The rate of change of frequency required for this equation is calculated using the Kalman filter. Once the total amount of load to be shed is estimated then the load to be shed from each bus is determined based on the PV analyses.

An optimization technique for load shedding [29] with distributed generation was developed. This technique converts differential equation into algebraic ones using the discretization method. Two cases are considered here; one with the distributed generation switched on to the system as a static model and the other case without the distributed generation on the grid. Both cases resulted in successful shedding of appropriate quantity of load.

Li Zhang suggests a method [30] which designs under frequency relays using both the frequency and the rate of change of frequency (df/dt). The scheme has been designed for a 50 Hz Northeast China power system. Traditional schemes required only the frequency decay information. Here the rate of change of frequency is used as auxiliary information. The plots for the rate of change of frequency are oscillatory in nature. Hence a new scheme is devised in this paper which considers the integration of the rate of change of frequency (df/dt) to indicate the frequency drop. By integrating one is effectively measuring the area between two frequencies, f_{i-1} and $f_{i.}$ The schemes is made up of five load shedding steps for a 50 Hz system. These steps are from 50 to 49.2 Hz, 49.2 to 49 Hz, 49 to 48.8Hz, 48.8 to 48.6 Hz, 48.6 to 48.4 Hz. The amount of load to be shed in each step is decided by integrating the df/dt value in each step. The simulation results when compared with the old scheme with just the frequency decay show a definite improvement in system frequency due to the inclusion of rate of change of frequency (df/dt) in the new scheme.

The main idea in the paper proposed by Xiong et al [31] is the inclusion of on line load frequency regulation factors. Loads with smaller frequency regulation factors are shed first, followed by the ones with larger frequency regulation factors. The active power and load frequency relation is established in the form of the following equation.

$$P_L = a_0 P_{LN} + a_1 P_{LN}\left(\frac{f}{f_N}\right) + a_2 P_{LN}\left(\frac{f}{f_N}\right)^2 + \ldots . a_n P_{LN}\left(\frac{f}{f_N}\right)^n \qquad (1)$$

Where, f_N is the nominal frequency. P_{LN} is the rated active power and a_i (i=1,2…n) is the percentage of the total load associated with the i-th term of the frequency.

The per unit form of the above equation is differentiated to get the change in load power as frequency changes (dP_L/df) which is the K_L factor or regulation factor. The higher order terms are neglected.

$$K_L = dP_L \big/ df = a_1 + a_2 * f + a_3 * f^2 \qquad (2)$$

Thus it is preferable to shed load for smaller regulation factors. Hence the loads are distinguished based on their individual regulation factors and accordingly load shedding schedules are planned based on their respective K factors.

Another scheme considering the rate of change of frequency is the adaptive load shedding algorithm in the paper by Seyedi et al [32]. Here the shedding is adapted as per the intensity of the disturbance. This intensity is determined based on the rate of change of frequency. Thus the main points observed while designing the scheme is that the speed of load shedding is increased if the rate of change of frequency (df/dt) values are high. Also, the number of load shedding steps and the amount of load to be shed in each step is increased if there is an increase in the rate of change of frequency (df/dt) values. The new method was tested on the HV network of the Khorasan province in Iran. The proposed method definitely showed improvements as compared to the conventional scheme.

Neural networks are proposed [33] to be used for an under frequency load shedding scheme. This intends to replace the conventional slow acting dynamic simulators by quick and efficient neural network engines. The general procedure is to identify the inputs for the neural networks, generations of data sets, designing NN and the evaluating the performance of neural nets. The variables used as inputs are the actual real power generation, available real power, actual load generation level prior to a disturbance, amount of the actual load being shed and the percentage of the exponential load to be shed.

A SCADA based scheme has been proposed by Parniani et al [34]. The rate of change of frequency is useful in identifying the overload when a disturbance occurs and hence is helpful to estimate the amount of load to be shed. The SCADA based scheme overcomes the shortcomings of the previous adaptive UFLS scheme. The mean system frequency is defined as follows,

$$f_i = \sum_{i=1}^{n} (H_i * f_i) / (\sum_{i=1}^{n} H_i) \qquad (3)$$

Where f_i is the frequency of the generators from 1 to n and H is their respective system inertia. Adding the df/dt equation every generator the post disturbance equation obtained for SCADA is,

$$\frac{d(\sum_{i=1}^{n} (H_i * f_i) / (\sum_{i=1}^{n} H_i))}{dt} = -60.\Delta P_L \Big/ (\sum_{i=1}^{n} 2Hi) \qquad (4)$$

where ΔP_L is the disturbance magnitude in per unit. Now another variable ΔP_{thr} is defined. If a disturbance occurring at the weakest generator is less than this value then the absolute frequency of that generator is within the permitted limits. For a situation where the disturbance magnitude, ΔP_L is less than ΔP_{thr} no load shedding is required. The maximum load shedding magnitude is equal to the difference between the disturbance magnitude and ΔP_{thr} (ΔP_L - ΔP_{thr}). The load to be shed is distributed inversely proportional to the generator inertia to make the load shedding most effective. The equation (4) represents this distribution.

$$\frac{1}{(n-1)}\frac{\sum_{k=1 k\neq i}^{n} H_i}{\sum_{i=1}^{n} H_i}(\Delta P_L - \Delta P_{thr}) \qquad (5)$$

Based on this equation the layers of the load shedding scheme are designed. Both the steps shed one third of the remaining load. These are in steps. They are presented in a table 4 with the first step being at 59.3 Hz.

TABLE 4: SCADA Based Load Shedding Formula

Frequency	Amount of Load to be shed	Delay
59.3 Hz	$\frac{1}{3*(n-1)}\frac{\sum_{k=1 k\neq i}^{n} H_i}{\sum_{i=1}^{n} H_i}(\Delta P_L - \Delta P_{thr})$	0.3 secs
58.5 Hz	$\frac{2}{3*(n-1)}\frac{\sum_{k=1 k\neq i}^{n} H_i}{\sum_{i=1}^{n} H_i}(\Delta P_L - \Delta P_{thr})$	0.2 secs

An adaptive load shedding scheme which includes a self healing strategy is presented by Vittal et al [35]. The proposed scheme is tested on a 179 bus 20 generator test system. This self healing strategy comes into play when the system vulnerability is detected. The system then divides into self sustaining islands. After this islanding, load shedding based on the rate of change of frequency is applied to the system. Due to this division, it becomes easier to restore load. A Reinforcement Learning scheme is discussed in the paper.

The first is the controlled islanding which is done using the two-time scale method. It deals with the structural characteristics of the power systems and determines the interactions of the generators and their strong or weak coupling. The Dynamic Reduction Program 5.0 (DYNRED) is the software in which simulations are run to implement this technique. Through this software coherent group of generators can be obtained on the power system.

Islanding causes two types of islands to be formed, the generation rich islands and the load rich islands. The load rich islands may have a further decline of frequency. This may result in the generator protection to trip the generators thus further declining the island's frequency. Thus a two layer load shedding strategy is employed for the load rich island. The first layer is based on the frequency decline approach. The second layer considers the rate of change of frequency. Due to the longer time delays and lower frequency thresholds for a frequency based scheme inadvertent load shedding is avoided. When the system disturbance is large and exceeds the signal threshold, the second layer comes into play. It sends a signal to discontinue the first layer of operation and continues with the load shedding based on rate of change of frequency. This layer will shed more load at the initial steps to prevent cascading effects. The magnitude of the disturbance is found based on the formula

$$\frac{df_i}{dt} = -\frac{60 x P_{sik}}{2H_i}(P_{L\Delta}(0^+) \Big/ \sum_{j=1}^{n} P_{sik}) \ . \qquad (6)$$

If we sum up all the equations for i=1 to n then the final equation obtained is

$$\frac{\overline{df}}{dt} = -\frac{60 x P_{L\Delta}}{\sum_{i=1}^{n} 2H_i} \qquad (7)$$

Where, m_0 is defined as $\frac{\overline{df}}{dt}$ which is the average rate of frequency decline. Rearranging the above equation we get a new equation which relates $P_{L\Delta}$ to m_0.

$$P_{L\Delta} = -m_0 x \sum_{i=1}^{n} 2Hi \Big/ 60 \qquad (8)$$

Since H_i is constant, the magnitude of m_0 can be directly proportional to the rate of frequency decline. Hence the rate of change of frequency ($\frac{\overline{df}}{dt}$) can be a measure of the disturbance. Once the disturbance threshold value, $P_{L\Delta}$, for the second layer of load shedding is decided, the m_0 value is calculated. The m_i at each bus is calculated and compared with m_0. If $m_i > m_0$ then the second layer is activated, otherwise the conventional load shedding scheme is used. This new shedding scheme increases the stability of the system by shedding fewer loads as compared to the conventional scheme.

Under Voltage Load Shedding Schemes

Under voltage load shedding relays are set up to operate in case of low voltage conditions in the system. Disturbance affected systems may retain their stability post disturbance but still have low voltages at buses. In the following paragraphs the deficiencies in reactive power in various cases have been discussed which also may result in cases of voltage instabilities. In certain cases the voltages might be too close to the stability limits and collapse can be so fast that simple under voltage correction schemes are not effective. These low voltage conditions can be corrected by shedding appropriate amount of load from buses with the help of effective under voltage load shedding schemes..

Lopes et all [36] suggests a method which carries out load shedding in case of two conditions. One, where the load shedding occurs due to a post disturbance low voltage condition and secondly, where the load shedding results due to the inability of the system to achieve a stable operating condition post disturbance. This method uses the load flow in order to decide the buses from which to shed load. The initial set of control actions are first carried out. These actions are capacitor switching, tap changing transformer and secondary voltage control.

Jianfeng et al [37] have developed a method with risk indices in order to decide which buses should be targeted for load shedding to maintain voltage stability. The buses with a high risk of voltage instability are considered first. This is estimated from the probability of a voltage collapse occurrence. The risk indices are the products of these probabilities and impact of voltage collapse.

Another method [38] dealing with the particle swarm approach for under voltage load shedding has been researched. The particle swarm Optimization concept is a group or cluster of particles in which each particle is known to have individual memory like an animal in its herd or flock. The flock is initiated with some initial velocity and the particles move in different directions to come up with the best solution. The best solution is shared with every particle of the group so that they can move from there on based on this new acquired knowledge. This same idea is used for under voltage load shedding to recognize the best possible load shedding scheme considering the system conditions and disturbance particular to that situation.

Ladhani and Rosehart [39] propose load modelling for an under voltage load shedding scheme. They also suggest offering economic incentives to customers for discontinuing the use of power during load control periods. This way the brunt of a sudden load shed is not borne by the customer alone. Also, systematic load control will lead to the stability of the system even when it is not faced with a disturbance.

There is another method for voltage control and setting up under frequency load shedding. It is proposed by Yorino et al [40] suggests a new planning method for planning the VAR allocation using the FACTS devices. Here, the total economic cost for a voltage collapse along with its corrective control and load shedding are taken into account to come up with the optimum VAR planning scheme. Thus, the objective function is to minimize the cost while keeping in mind the voltage stability of the system.

Mozino [41] discusses the currently existing under voltage load shedding schemes. They are divided into two categories; decentralised and centralised. The decentralised load shedding involves setting relays at buses with loads to be shed and tripping the respective relays. The centralised scheme is more advanced. The relays are installed at the key bus locations and the information regarding which relays are to be tripped is sent to these relays from a main control centre. Thus the required load is shed from appropriate buses. Many of these schemes are referred to as “special protection” or “wide area” schemes.

The two categories mentioned above are widely used as under voltage load shedding relays. These relays require logic and have to perform efficiently and accurately. Also, these relays must avoid false operation. Thus to satisfy the above requirements digital relays are being used for under voltage load shedding. Two schemes using digital relays are discussed in the paper by Mozina [41].

Single Phase UVLS Logic measures voltages on every phase. This scheme distinguishes between voltage collapse and fault induced low voltages. The voltage collapse is a balanced phenomenon, hence results in a reduction of voltage on all the three phases. Except for a three phase fault all the other faults are unbalanced. The relays trips when it identifies a voltage collapse and blocks the relay for a fault induced low voltage. Unbalanced faults usually induce negative sequence voltages which are detected and used for blocking the relay.

Positive sequence UVLS logic checks the positive sequence voltage with the set point value. Since the voltage collapse is balanced for all the three phases, the positive sequence voltage is equal to the three phase voltages. In case of a fault condition, the negative sequence voltage is utilised to block the relay.

Based on the 2004 blackout and the Voltage Assessment system for voltage instability the Hellenic Transmission System Operator (HTSO) decided to automate the load shedding process. In the following paper [42] two load shedding strategies are described. The first one is in the Athens region and the second one is in the Peloponnese area. For the first scheme in Athens, an event driven Special Protection Scheme (SPS) was set up. This scheme used the already existing protection scheme to check for overloads in the northern interconnections. The table 5 describes the set up of the scheme. The trip commands 2 and 3 are for voltage instability.

TABLE 5: Load Shed By The Hellenic Transmission System Operator

Tripping Commands	Estimated Load Shedding (MW)	Measured Load Shed on June 22, 2006 (MW)
1	90	24
2	170	158.6
3	190	155.8
4	120	120.2
5	100	68.4
6	75	65.4
7	150	N/A
8	80	N/A
TOTAL	**975**	**592.4**

A sudden disconnection of a 400 KV line on June 22nd caused the protective scheme to trigger the automatic load shedding as shown in Table 5. Though the scheme was set with eight tripping steps, the actual load shed was lesser than the estimated value. Also, the trip commands 7 and 8 were not applied in the automatic scheme. For the voltage to remain stable, the actual amount of load shed on June 22nd is taken to be the amount and not the estimated value.

In the Peloponnese area automatic load shedding occurs when specific transmission lines trip. A manual load shedding procedure is to follow this automatic set up. At present this shedding scheme is implemented when two 150 KV lines starting from the Megalopolis area are disconnected. The manual load shedding increases the reliability of the protection system.

A load shedding scheme against long term voltage instability is proposed in this paper by Van Cutsem et al [43]. It uses distributed controllers which are delegated a transmission voltage and a group of loads to be controlled. Each controller acts in a closed loop, shedding loads that vary in magnitude based on the evolution of its monitored voltage. Each controller acts on a set of electrically close loads and monitors the voltage V of the closest transmission bus in that area. The controller is rule based where the rules are simple if-then statements. For example, if voltage reduces below V^{th} , then load will be shed equal to ΔP^{sh} . This is just an example. The actual scheme is explained as follows. The controller decides to shed load based on the comparison between voltage V of that area to the threshold value V^{th} . This threshold value can be pre decided by the operations personnel based on empirical system data. If V is below the threshold value, then the controller sheds load ΔP^{sh} of the load power after a delay of time τ . Both ΔP^{sh} and τ depend on the dynamic evolution of V. If t_0 is the time when V decreases below V^{th} , the first block of load to be shed is at a time $t_0+\tau$ such that

$$\int_{to}^{to+\tau} (V^{th} - V(t))dt = C \tag{9}$$

The difference in the actual voltage and the threshold value over the time period τ is integrated. Here the value of τ is to be determined. C is a constant, predetermined by empirical data, on which the time delay τ depends. The larger the value of C, the more time it takes for the integral to reach this value and hence more is the time delay. Similarly for a larger dip in the voltage from the threshold value, the integral takes less time to reach C, hence the time delay is also less. The amount of load to be shed by the controller at time $t_0+\tau$ is

$$\Delta P^{sh} = K.\Delta V^{av}. \tag{10}$$

Here, ΔV^{av} is the average voltage over the [t_0 , $t_0+\tau$] interval. K is the empirical constant which relates the amount of load to be shed to the average voltage. This can be further expressed as;

$$\Delta V^{av} = \frac{1}{\tau}\int_{t_o}^{t_o+\tau}(V^{th} - V(t))dt \qquad (11)$$

Thus larger the $V^{th} - V(t)$ difference, larger the ΔV^{av} value and thus larger is the load shed.

Thus the various conventional schemes, under frequency schemes and under voltage load shedding schemes have been discussed above. These give an insight about the technological advancement achieved in this area. The proposed scheme in this thesis incorporates frequency and voltage together and tries to overcome some of the disadvantages faced by the conventional schemes present in the industry.

CHAPTER 3

PROPOSED LOAD SHEDDING SCHEME

The following chapter discusses the proposed load shedding scheme and the algorithm. This has been the main objective of the thesis. The load shedding scheme mainly has included the measurement of important parameters for estimating the magnitude of disturbance. The initial estimation of the disturbance is based on the rate of change of frequency. The location of the load to be shed and the amount to be shed from each bus is calculated by the empirical formula. This formula is based on the voltage sensitivities calculated using the QV analysis. The disturbance which has been modeled here is explained in details. There is also a brief idea about the problems and concerns encountered while developing this scheme. This is followed by the description of the test system used and its modeling in PSSE. The observations and results obtained are presented in the following chapter.

Methodology for the proposed load shedding algorithm

Referring to chapter 1, the load shedding scheme proposed here has incorporated two parameters, the frequency and the bus voltages, for deciding the instant, the amount and the location of the load to be shed. The scheme developed here consists of a stepwise approach. This has been represented in the form of an algorithm.

The first step is the measurement stage which has been discussed in chapter 3. When a disturbance causes a deviation in frequency or a change in bus voltage or both, it is recorded and the magnitude of the disturbance is estimated using the swing equation. This estimate determines the amount of load to be shed. Once, the quantity of load to be shed is decided, the buses are ranked according to their dV/dt values. This ranking decides the order in which load will be shed. Thus the bus where the voltage is declining at a faster rate has a higher dV/dt value and is ranked at a higher position. Once the order of the shedding is decided the next stage calculates how much load needs to be shed from each load bus. This is decided by a formula based on the voltage sensitivities.

The first step of the load shedding procedure is the measurement and calculation of the rate of change of frequency. Depending on the relay, the frequency measurements or the rate of change of frequency are recorded in the system. The PSS/E software has the provision for plotting the rate of change of frequency once the frequency is recorded. For the research cases shown below, the average value of the df/dt is calculated at the point where the frequency declines below 59.7 Hz. For example in the case where the generator at bus 30 is lost, the plot for the rate of change of frequency is not a smooth graph, it consists of oscillations. This plot is shown in figure 2.

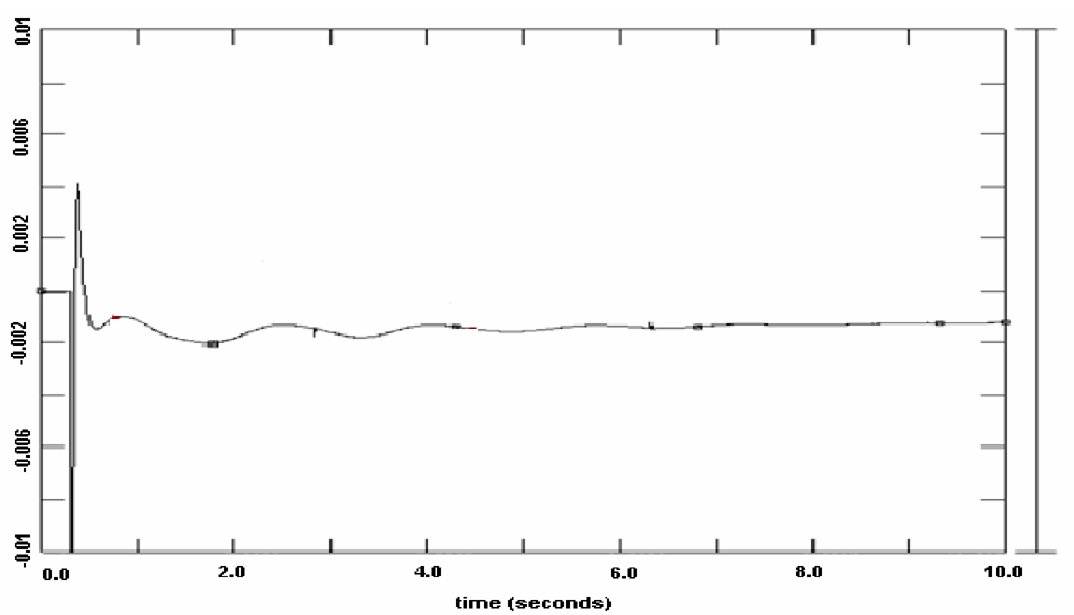

Fig.2 Instantaneous rate of change of frequency

The absolute value on any point on this graph will not give the correct df/dt value at that point. Hence the average of the values from the time the disturbance occurs up to the point where the frequency just drops below 59.7 Hz is considered for taking the average df/dt. The average rate of change of frequency plot is shown in figure 3. From this the desired df/dt value is used to calculate the estimated disturbance magnitude.

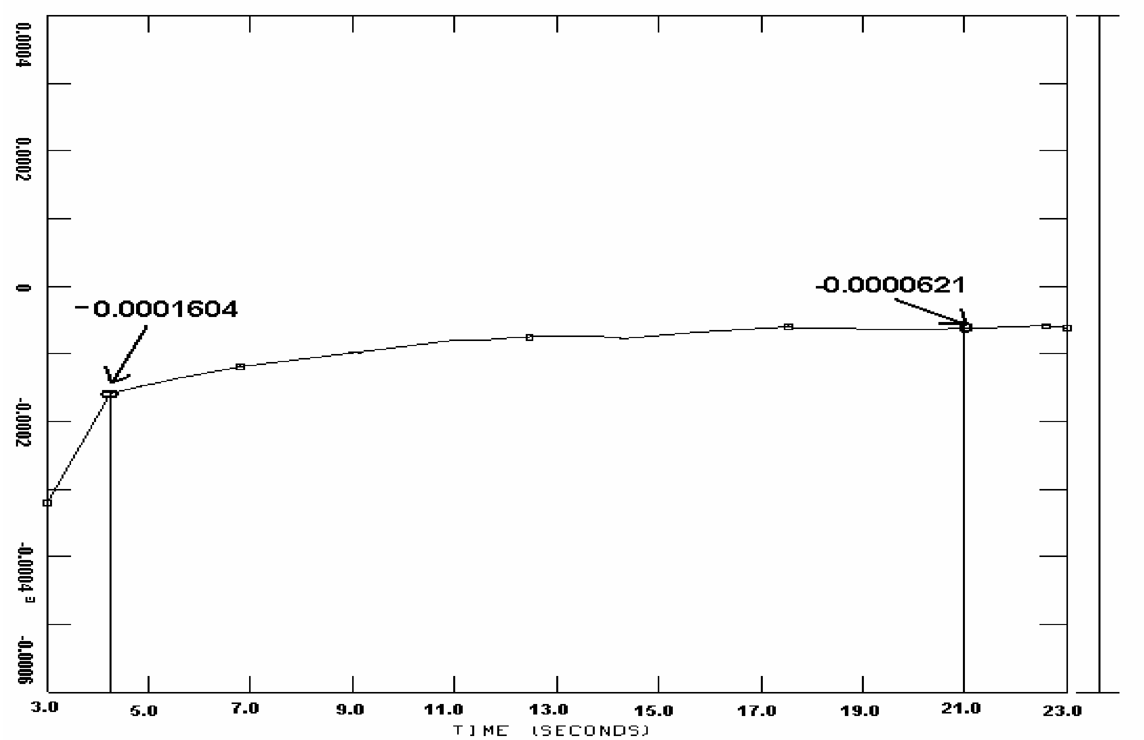

Fig.3 Average rate of change of frequency.

The main approach of the load shedding technique is discussed as follows. Initially at steady state all the dQ/dV, voltage sensitivities can be calculated for the system. From this, the voltage stability limit is known. Now, during a disturbance the voltage or frequency may start dropping below the limits. In this case the frequency limit is considered to be 59.7 Hz below which load shedding will start. The reason for selecting this pick up value is that a survey of the existing load shedding techniques was done, an overview of which was presented in Chapter 2. Based on this, the standard frequency pick up value in the industry to begin a load shedding procedure is 59.7 Hz on a 60 Hz system and 49.7 Hz on a 50 Hz system.

The first step of the algorithm is estimating the total load mismatch between the generated power and load power. This can be determined as follows. For a single machine, the swing equation [1] is given by

$$\frac{2H}{f_0}\frac{df}{dt} = P_m - P_e = P_{diff} \tag{12}$$

where, f_0 is the nominal frequency of the system and P_{diff} is the difference in the generated power and the load power. In the above equation ω is replaced by f since $\omega = 2\pi f$. Thus a relation between the frequency and the power mismatch is obtained. This relation establishes the estimated magnitude of the disturbance. The inertia constant in the above equation is the kinetic energy W_k over the system base MVA. The inertia constants of all the machines in the system are on the base MVA.

The above swing equation is for a single machine. In a large power system there are many generators which maybe geographically far away from each other. In such a case it is desirable to reduce the number of swing equations. Thus the generators which swing together can be coupled together and a single equivalent swing equation is written for them. These generators are known as coherent generators. For example, consider an n generator system. These are geographically spaced over a large area, as is the case with a real power grid. But when this system is affected by a disturbance such as a fault, all the generator rotors swing coherently. Their individual swing equations are given below. The inertia constant H for each machine is represented as $H_1, H_2, H_3 \ldots. H_n$. The mechanical shaft power and the electrical power for each machine is represented as P_{m1}, P_{m2}, P_{m3} …. P_{mn} and P_{e1}, P_{e2}, P_{e3} ….. P_{en} .The swing equations for each individual machine are;

$$\frac{2H_1}{f_0}\frac{df_1}{dt} = P_{a1} = P_{m1} - P_{e1} \text{ for machine 1} \tag{13}$$

$$\frac{2H_2}{f_0}\frac{df_2}{dt} = P_{a2} = P_{m2} - P_{e2} \text{ for machine 2} \tag{14}$$

$$\frac{2H_3}{f_0}\frac{df_3}{dt} = P_{a3} = P_{m3} - P_{e3} \text{ for machine 3…………} \tag{15}$$

and so on $$\frac{2H_n}{f_0}\frac{df_n}{dt} = P_{an} = P_{mn} - P_{en} \text{ for machine n} \tag{16}$$

The equivalent inertia constant of the two machines is the summation of the individual inertias of each machine.

$$Heq = \sum \textit{individual inertias of each machine for all the machines in the system}$$

Also, the equivalent mechanical and electrical powers are given as;

$$Pm = \sum \textit{individual mechanical shaft power of each machine for all the machines in the system}$$
$$Pe = \sum \textit{individual electrical power of each machine for all the machines in the system}$$

This can be represented mathematically as follows. The equivalent inertia is;

$$H_{eq} = (H_1 + H_2 + H_3 + \ldots\ldots H_n) \tag{17}$$

The equivalent mechanical shaft power and electrical power are given as follows;

$$P_m = (P_{m1} + P_{m2} + P_{m3} + \ldots\ldots P_{mn}) \tag{18}$$

$$P_e = (P_{e1} + P_{e2} + P_{e3} + \ldots\ldots P_{en}) \tag{19}$$

Once the magnitude of the disturbance is determined using the above equivalent swing equation, the location and the amount of load to be shed from each bus has to decided. In order to do this, the buses are ranked according to the dV/dt values at the point of detection of frequency decline. The bus with the largest dV/dt is listed at the top of the list and then so on in the decreasing order. Once the order is decided, the next step is to decide the amount of load to be shed at each bus.

This is decided based on the voltage sensitivity at each bus. Thus the bus with voltage sensitivity very close to the instability limit will have a maximum load shed based on the reciprocal of its sensitivity as a fraction of the sum of the reciprocals of all the load bus sensitivities. Now the QV analysis is carried out in the following manner. The equations for active and reactive power are,

$$P_i = \sum_{j=1}^{n} V_i V_j Y_{ij} * \cos(\delta_{ij} - \theta_{ij}) \tag{20}$$

$$Q_i = \sum_{j=1}^{n} V_i V_j Y_{ij} * \sin(\delta_{ij} - \theta_{ij}) \tag{21}$$

On simplifying it further for a two bus system the equations will be;

$$P_{12} = |V_1|^2 G - |V_1||V_2| G * \cos(\delta_{12}) + |V_1||V_2| B * \sin(\delta_{12}) \tag{22}$$

$$Q_{12} = |V_1|^2 B - |V_1||V_2| B * \cos(\delta_{12}) - |V_1||V_2| G * \sin(\delta_{12}) \tag{23}$$

Now at the receiving end the power delivered is

$$P_D = -P_{12} \text{ and } Q_D = -Q_{12}\,. \tag{24}$$

Hence the QV curves are plotted for given values of P_D and V_2 to compute θ_{12} and from this the value of Q_D is calculated from the second equation. Although this is only for a two bus system, the same procedure is followed for a larger system.

Now once the equation between Q_D and V_2 is established, differentiating the above equation we get,

$$\frac{dQ_D}{dV_2} = V_2 * B\cos\delta_{12} + V_2 * G\sin\delta_{12} \tag{25}$$

This is for a two bus system. For a n bus system the generalized equation is,

$$\frac{dQ_i}{dV_i} = \sum_{j=1}^{n} V_j Y_{ij} * \sin(\delta_{ij} - \theta_{ij}) \tag{26}$$

Thus individually for each bus the relation dQ/dV relation can be written as;

$$\frac{dQ_1}{dV_1} = \sum_{j=1}^{n} V_j Y_{1j} * \sin(\delta_{1j} - \theta_{1j}) \tag{27}$$

$$\frac{dQ_2}{dV_2} = \sum_{j=1}^{n} V_j Y_{2j} * \sin(\delta_{2j} - \theta_{2j}) \text{ …and so on till} \tag{28}$$

$$\frac{dQ_n}{dV_n} = \sum_{j=1}^{n} V_j Y_{nj} * \sin(\delta_{nj} - \theta_{nj}) \tag{29}$$

Plotting the dQ/dV for one such sample bus, the following Q-V plot shown in Fig.4 is obtained. The knee point of the plot denotes that the system is in a critical situation and is unstable beyond that point. As the knee point is approached, the dQ/dV values become smaller. Thus a system bordering on instability will have a small value of the slope at the knee point.

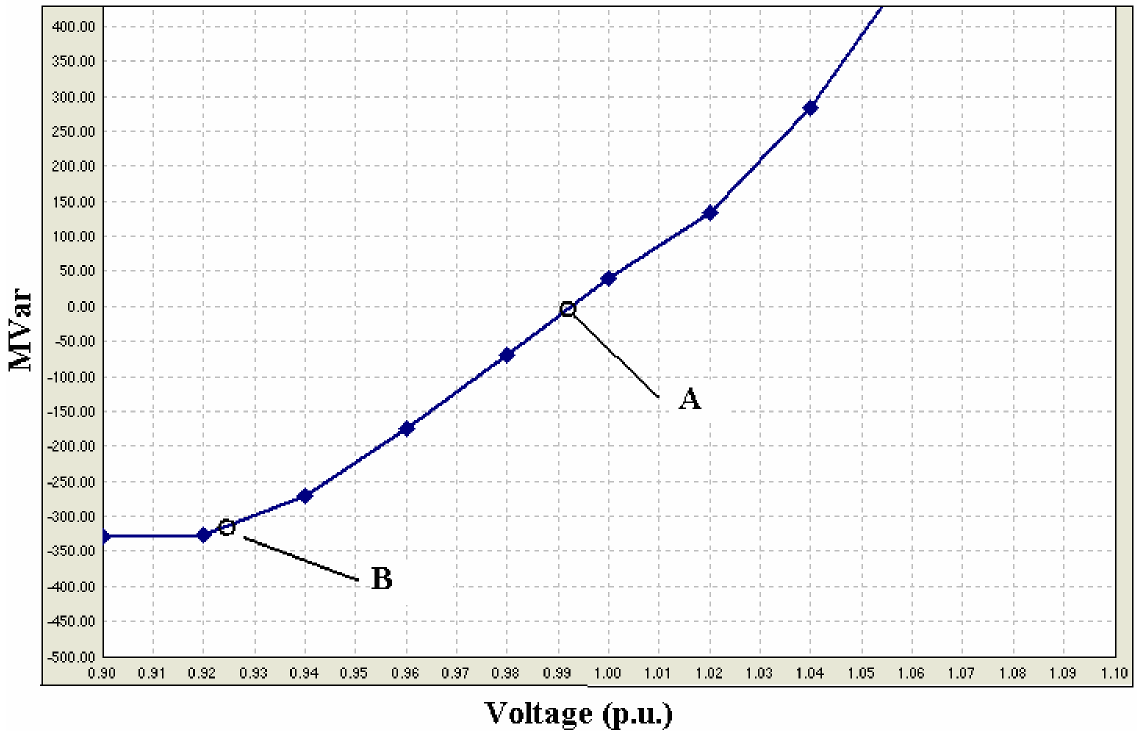

Fig. 4 Q-V analysis, Q Mvar on the Y-axis and voltage in p.u. on the X-axis

The plot in figure 4 considers two point A and B which represent two states of voltage stability. Here in the above figure, The Y axis is the Mvar values of Q and the X axis is the p.u. values of the bus voltage at a certain bus. As can be seen, the point B is closer to the knee point as compared to point A. Thus the dQ/dV of point A will be higher than the dQ/dV of point B. Thus more load needs to be shed from a bus with the dQ/dV value of point B. Thus,

$$\frac{dQ_i}{dV_i} \propto \textit{(1/ Amount of load to be shed from each bus)} \qquad (30)$$

In order to estimate this load quantity we consider the reciprocal of the voltage sensitivity as a fraction of the sum of all the reciprocals of voltage sensitivities. The reciprocal is considered because for a higher slope (i.e. a more stable case), the reciprocal will be smaller, hence a lesser amount of load will be shed from it. Thus it can be said that,

$$\boldsymbol{\frac{dV}{dQ}} = (1 \Big/ \frac{dQ}{dV}) . \tag{31}$$

$$\boldsymbol{\frac{dV_i}{dQ_i} = (1 \Big/ \sum_{j=1}^{p} V_j Y_{1j} * \sin(\delta_{1j} - \theta_{1j}))} \tag{32}$$

The above equation gives a fractional value of the voltage sensitivity for each bus. Now there is a direct relation between the amount load to be shed and the dV/dQ value at each bus.

$$\boldsymbol{\frac{dV_i}{dQ_i} \propto \textit{(Amount of load to be shed from each bus)}} \tag{33}$$

Hence closer a bus is to the knee point lower higher will be the dV/dQ value. Now, the summation of the dV/dQ values of all the buses is ,

$$\sum_{i=1}^{n} \frac{dV_i}{dQ_i} = \frac{dV_1}{dQ_1} + \frac{dV_2}{dQ_2} + \ldots\ldots \frac{dV_n}{dQ_n} \tag{34}$$

The above equation gives the summation of the dV/dQ values at all the load buses. The load shed at each bus is a fraction of the total load required to be shed to maintain the power balance. This fraction of load at each bus is proportional to the fraction of the dV/dQ value at each bus with respect to the sum total calculated above. This is represented as

$$\frac{\frac{dV_i}{dQ_i}}{\left(\frac{dV_1}{dQ_1} + \frac{dV_2}{dQ_2} + \ldots\ldots \frac{dV_n}{dQ_n}\right)} \quad \text{for each bus i.} \tag{35}$$

This is the fraction of the total voltage sensitivities. Thus closer the bus 'i' is to the knee point of the Q-V curve higher will the value of the above fraction be. Hence when this fraction is multiplied by the total amount of load to be shed, the load to be shed from each bus is obtained based on how close that bus is to the knee point. Thus as shown in Fig.4, for a point B, the fraction $\dfrac{\frac{dV_i}{dQ_i}}{(\frac{dV_1}{dQ_1}+\frac{dV_2}{dQ_2}+......\frac{dV_n}{dQ_n})}$ is higher than that of point A. Thus more load is shed from a bus at point B which is desirable since this bus is critical from the voltage stability point of view. Thus the empirical formula to be tested out is;

$$\boldsymbol{S_i = \frac{\left(\frac{dV_i}{dQ_i}\right)}{\left[\sum_{i=1}^{n}\left(\frac{dV_i}{dQ_i}\right)\right]} P_{diff}} \tag{36}$$

The algorithm for the proposed scheme is in figure 5.

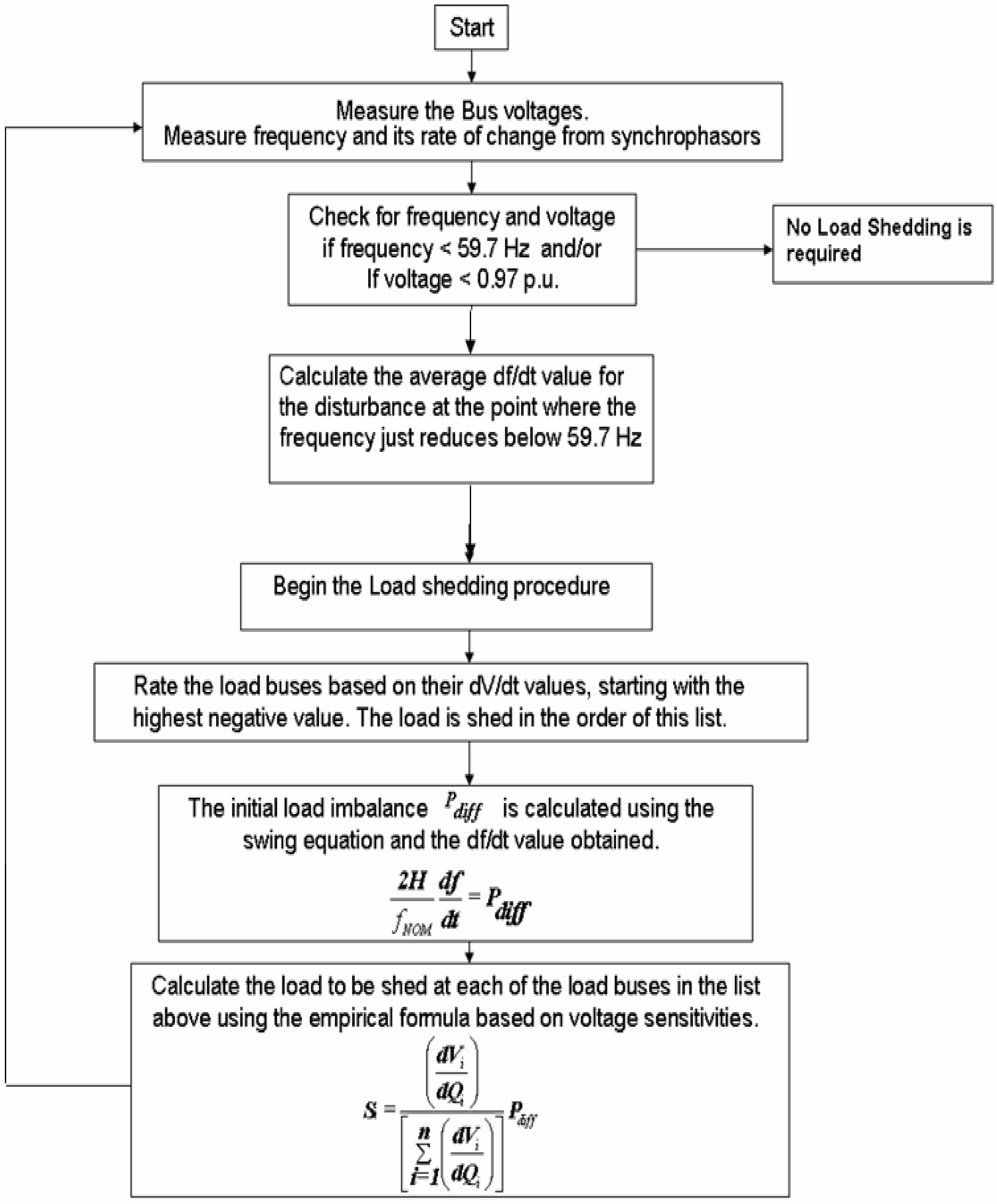

Fig. 5 Load Shedding Algorithm

Test System Modeling in PSSE

There are two test systems considered for this thesis. These are the 39 bus system and the 145 bus system provided by IEEE. The system data for the IEEE 39 bus system was in the PTI format as approved by PSSE-30. For the 145 bus system, the system data was in the IEEE Common data format which was converted to the PTI format using one of the utilities provided by PSS/E-30. The dynamic simulations are carried out in the dynamic activity selector of the PSSE-30 software. The PSSE software is used frequently in the industry and hence is equipped to handle a variety of power system grids. The codes and subroutines for PSSE are written in the FORTRAN language.

The 39 bus sample system consists of 39 buses and 10 generating units out of which one is the swing bus. The data given with the sample system is the generator data - including the time constants and the inertia constants, the transmission line data - the line impedances and branch connections and the load data. Similarly, the 145 bus system consists of 145 buses and 50 generators. The data provided for this is also the power flow data along with the generator and exciter data. The single line diagram of the system is shown in figure 6.

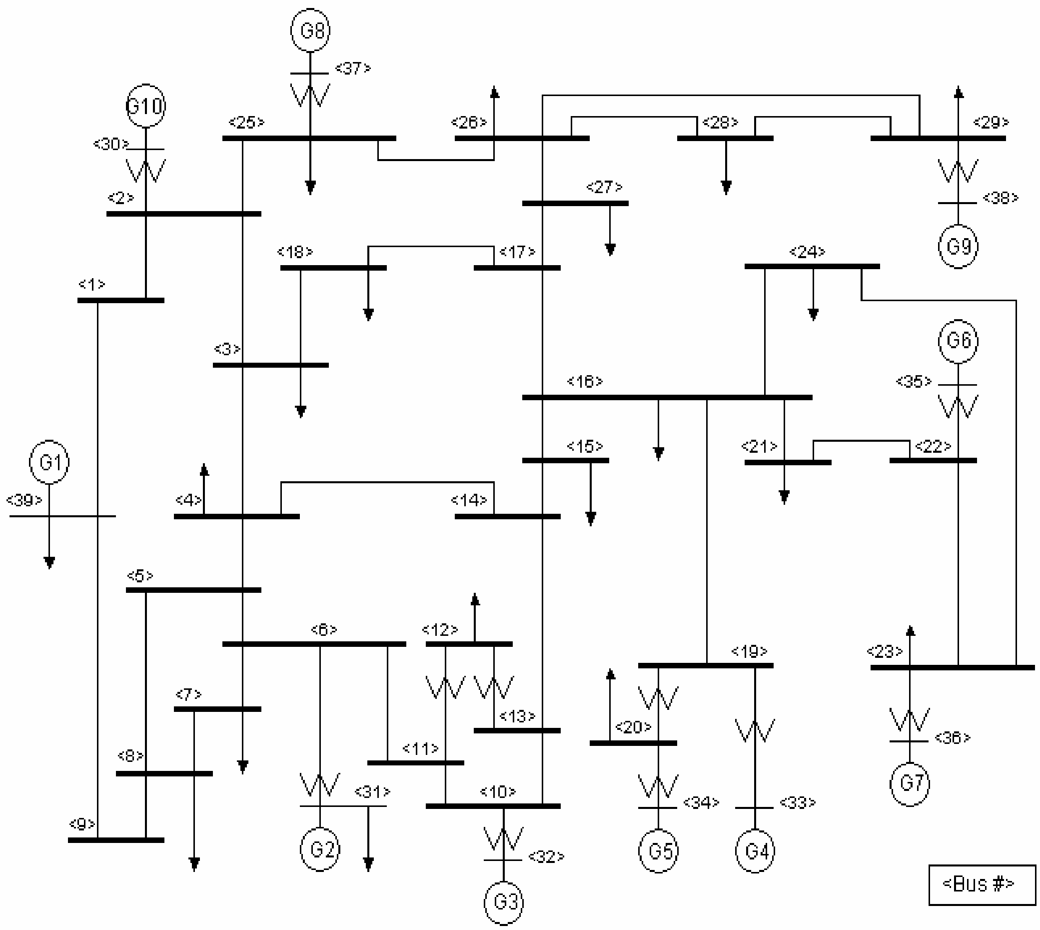

Fig.6 IEEE 39 bus system

The preceding section discussed the test system and the PSS/E software, in which dynamic simulations are carried out. It is important to state that power systems being such a wide area network of various transmission lines and equipments, it is subject to innumerable types of faults and disturbances. It is physically impossible to simulate all of these. Hence for the concerned research presented here, two typical disturbances namely the loss of a generator and the loss of a transmission line are modelled. The sudden loss of a generator results in the loss of generated power, it presents a situation suited for the operation of the load shedding scheme. There are six cases (each with a different generator) considered for the IEEE 39 bus system and ten cases considered for the 145 bus system. In each case the loss of a generator is modelled and the system is observed before and after implementing the load shedding scheme. There are two cases observed, the stable and the unstable. During the stable case, the system is stable in spite of the generator loss but the frequency and voltage decline below their lower limits. The unstable case is caused due to the rotor angle instability after the generator loss. In both these cases when load shedding is implemented in time, the system is prevented from becoming unstable and the frequency and voltages are maintained within their prescribed limits.

The second disturbance modelled is the loss of a transmission line for the IEEE 39 bus system. The various critical lines are listed and the scenario in each case is studied. The system response to each case is recorded and the important observations are presented in the next chapter.

Thus the observations and results in the following chapter are for the loss of a generator at various buses, although it has been kept in mind that the load shedding scheme follows a general format and can be utilized for any disturbance demanding the initiation of load shedding.

CHAPTER 4

OBSERVATIONS ON THE IEEE TEST SYSTEMS

The proposed load shedding scheme has been tested on the IEEE test systems described in the previous chapter. For each of the test system different test cases are considered. Two types of disturbance cases are considered. The first disturbance case considered is the loss of a generator. For each IEEE test system the loss of a generator is modeled. Similarly for the second disturbance case, which is the loss of a transmission line, various test cases are simulated and the results are observed. The following chapter contains the results and the plots obtained before and after the load shedding scheme is applied. PSS/E software has been used for simulating the dynamic of the disturbance and presenting the frequency and voltage plots before and after the implementation of the load shedding scheme.

Case study 1: Loss of a generator for the IEEE 39 bus system

The Case Study 1 of the IEEE 39 bus system considers the loss of a generator at bus 30 causing a reduction in the total generated power of the system by 250 MW. The calculated disturbance magnitude using the swing equation based on the df/dt values is determined to be approximately 250.3 MW. The resulting frequency plot after the disturbance and without load shedding is shown in Fig.12. The case discussed below is to explain the procedure of the proposed load shedding algorithm.

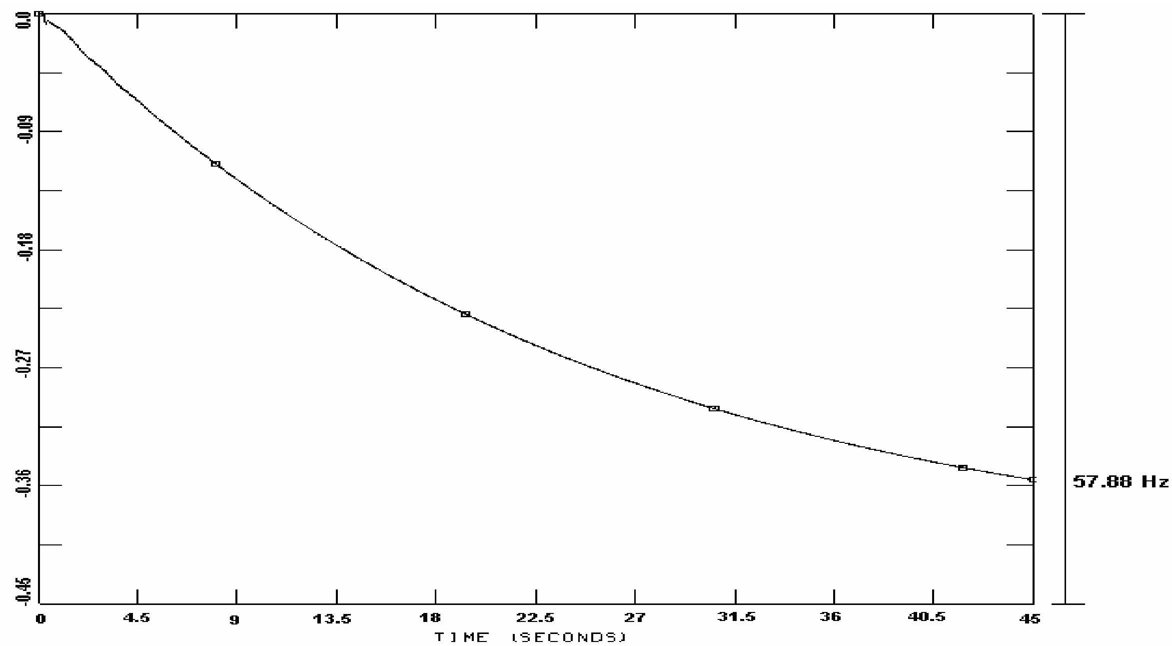

Fig. 7 IEEE 39 bus system: Average System Frequency (without load shedding)

The generator loss causes the frequency to decline which can be seen in the plot of figure 12. Without load shedding the frequency stabilizes at a value much lower than the required standard limits, which is 57.88 Hz in this case. Thus it becomes necessary to improve the frequency plot.

Besides the frequency, the voltages are also affected if there is a loss in the generated power. This can be seen based on the plots of some of the critical bus voltages in the figure 13 before the use of the load shedding scheme. The voltages decrease below their predetermined standards and stabilize at a lower value.

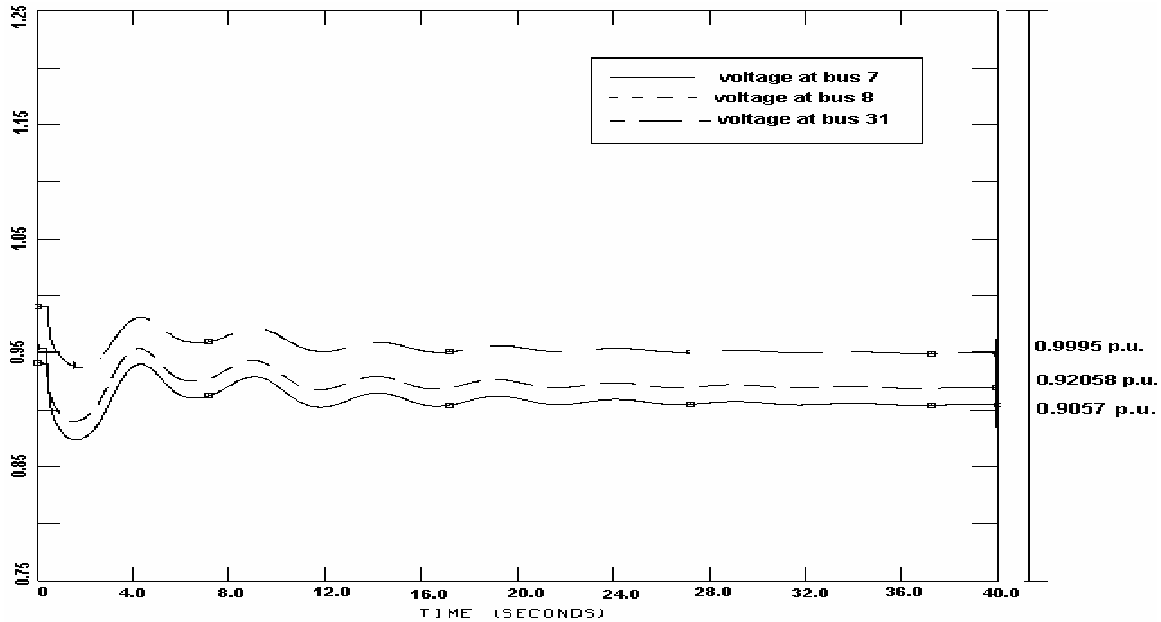

Fig. 8 IEEE 39 bus system : Voltages at bus 7,8 and 31 without the load shedding scheme.

While testing the proposed algorithm on test systems, certain system time delay needs to be considered. The propagation time and time delays of the actual system can be simulated during the testing of the algorithm. These time delays are translated into relay triggering times while testing the IEEE test systems. Thus as soon as the frequency begins to decrease below the threshold value of 59.7 Hz, the relays begin operation within 0.5 secs. Simultaneously, the necessary calculations for the disturbance magnitude are conducted using the swing equation and the df/dt values obtained from the synchrophasors. In addition, amount of load to be shed from each bus is also estimated during this time delay by ranking each based on its voltage sensitivities. These dV/dQ values are calculated individually for each load bus. These results are listed in Table 6.

TABLE 6: Voltage Sensitivities At Each Load Bus For IEEE 39 Bus System (Case Study 1)

Bus number	dQ/dV	dV/dQ
3	8750	0.0001143
4	7000	0.0001428
7	6000	0.0001667
8	9100	0.00010989
15	5000	0.0002
16	7500	0.0001333
18	9200	0.0001087
20	9800	0.00010204
21	10000	0.0001
23	10000	0.0001
24	9583	0.00010435
25	10000	0.0001
26	7000	0.0001428
27	5555	0.00018
28	4000	0.00025
29	7300	0.00013698
31	10000	0.0001
39	10000	0.0001

The individual dV/dQ values are calculated in the table above. The summation of all these dV/dQ values is **0.0023915**. This value is utilized in the voltage sensitivity formula in order to calculate the load to be shed at each bus. Thus the load shed at each bus according to the voltage sensitivity formula by substituting appropriate values.

$$S_i = \frac{\left(\frac{dV_i}{dQ_i}\right)}{\left[\sum_{i=1}^{n}\left(\frac{dV_i}{dQ_i}\right)\right]} P_{diff} \tag{37}$$

The results obtained using this formula are tabulated in table 7.

TABLE 7: Load shed at each bus for IEEE 39 bus system (Case Study 1)

Bus number	Load shed based on sensitivity formula (MW)
3	11.95
4	14.93
7	17.43
8	11.49
15	20.91
16	13.93
18	11.36
20	10.67
21	10.45
23	10.45
24	10.91
25	10.45
26	14.93
27	18.82
28	26.13
29	14.32
31	10.45
39	10.45

The total load shed is 250.3 MW. The resulting frequency and voltage waveforms are shown below. The load is shed in increments of 0.05 seconds so that a sudden loss of load does not occur. By increasing the number of steps and shedding load in small steps, excessive shedding is avoided. After applying the load shedding algorithm, the frequency and the voltages plots are shown in the Fig 9-10.

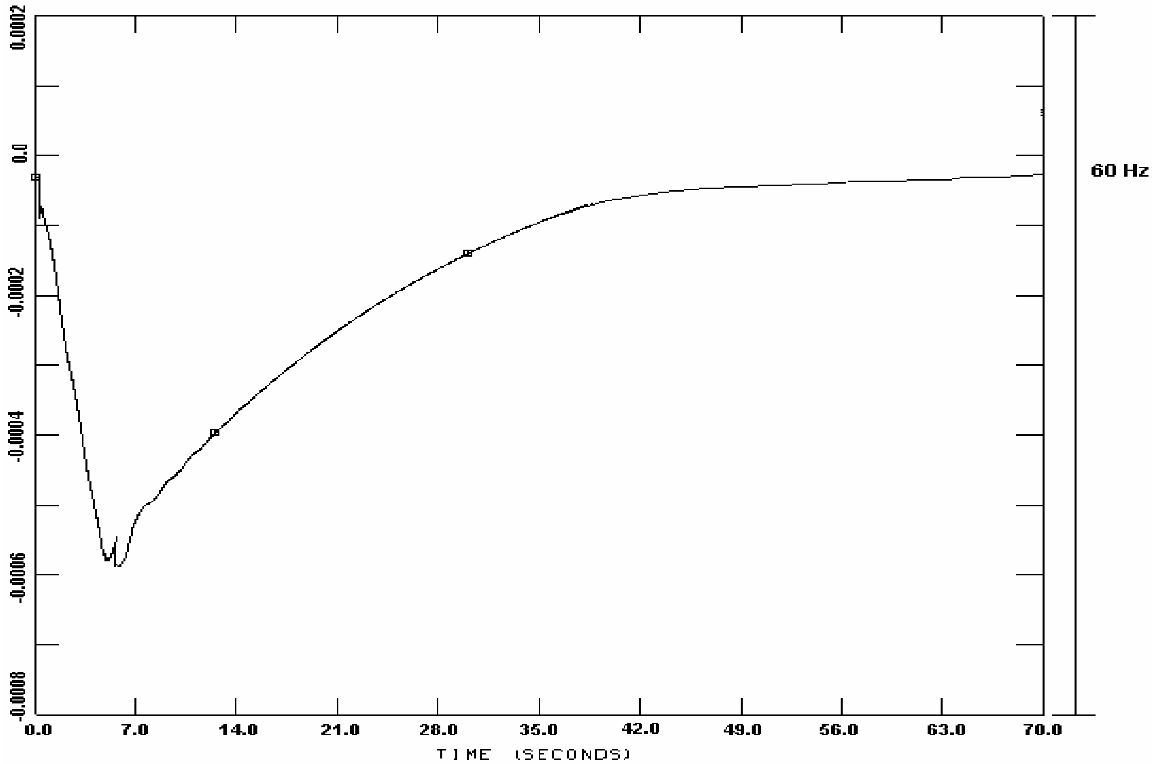

Fig.9 IEEE 39 bus system : Frequency for Case study 1 after applying Load shedding

The frequency improves above the specified lower limit. It settles at a value close to 60 Hz. The voltage plots show an improvement as well. In fact the final voltage values of the critical buses shown in figure 15 have been improved due to the appropriate amount of shedding.

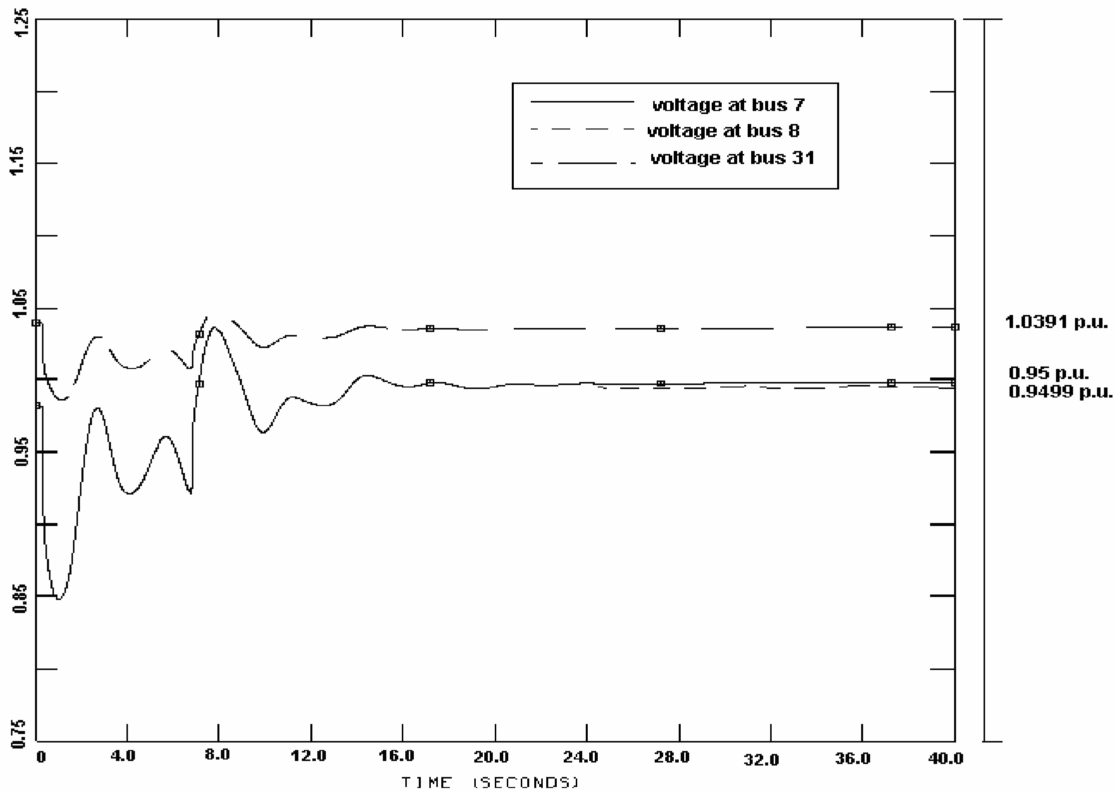

Fig. 10 IEEE 39 bus system : Voltages at buses 7,8 and 31 after load shedding.

The frequency before the implementation of the proposed scheme fell to a value of 57.88 Hz, has now improved to 59.89 Hz within 25 seconds reaching an acceptable value of 59.98 after applying the load shedding scheme. The voltage profile also shows a significant improvement. The pre-load shedding low value of 0.89 p.u. has now improved to 0.96 p.u.

Test cases for IEEE 39 bus system: Loss of a generator

The sample test case shown in the previous section serves the purpose of presenting a detailed implementation of the proposed load shedding technique. There were other cases considered to check how the system reacts to different generator losses.

The observations made on the unstable cases have been presented below. The various disturbance cases have been tabulated below in table 8.

TABLE 8: IEEE 39 bus system disturbance test cases

Generator Lost	Generation MW lost	Post disturbance frequency	System State	Time after which system becomes unstable
32	650	58.55 Hz	Unacceptable	1.6917 sec
33	632	55.09 Hz	Unacceptable	36.27 sec
34	508	55.2 Hz	Acceptable	-
35	650	53.94 Hz	Acceptable	-
36	560	54.96 Hz	Acceptable	-
37	540	54.77 Hz	Acceptable	-

The table 9 shows the post disturbance frequency and the system state for the loss of a single generator at six different buses. For each of the above disturbance cases the load shedding algorithm is applied and the load to be shed from each bus is estimated based on the voltage sensitivity formula as explained in Case study 1. On shedding this load an improved frequency and voltage profile is obtained. The results for all the six cases are presented below in one tabulated format in table 9.

TABLE 9: Load shed at each bus for each test case of the IEEE 39 bus systems

Bus no.	Load estimate (loss of Gen 32)	Load estimate (loss of Gen 33)	Load estimate (loss of Gen 34)	Load estimate (loss of Gen 35)	Load estimate (loss of Gen 36)	Load estimate (loss of Gen 37)
3	31.062	30.201	24.276	31.062	26.761	25.805
4	38.807	37.732	30.329	38.807	33.433	32.2393
7	45.302	44.047	35.405	45.302	39.029	37.6351
8	29.863	29.036	23.339	29.863	25.728	24.8094
15	54.351	52.846	42.477	54.351	46.825	45.1531
16	36.225	35.222	28.311	36.225	31.209	30.0946
18	29.54	28.722	23.086	29.54	25.45	24.5407
20	27.73	26.962	21.672	27.73	23.89	23.0371
21	27.176	26.423	21.239	27.176	23.413	22.5766
23	27.176	26.423	21.239	27.176	23.413	22.5766
24	28.358	27.572	22.163	28.358	24.431	23.5587
25	27.176	26.423	21.239	27.176	23.413	22.5766
26	38.807	37.732	30.329	38.807	33.433	32.2393
27	48.916	47.561	38.23	48.916	42.143	40.6378
28	67.939	66.057	53.097	67.939	58.532	56.4414
29	37.225	36.194	29.093	37.225	32.071	30.9254
31	27.176	26.423	21.239	27.176	23.413	22.5766
39	27.176	26.423	21.239	27.176	23.413	22.5766

The table 9 presents the load to be shed at each bus due to the loss of different generators. Without load shedding, some of the above cases may result in unacceptable voltage and frequency plots after certain generators are lost. These two cases are, when the generators at buses 32 and 33 are lost. The frequency is dropped below the desired point to 58.55 Hz and 55.09 Hz respectively in both the cases. Thus it is necessary to apply load shedding as soon as the disturbance is detected. The total time required on an average to start shedding load is 0.3 seconds. As soon as the shedding process starts the system frequency immediately starts rising and thus prevents unstable conditions.

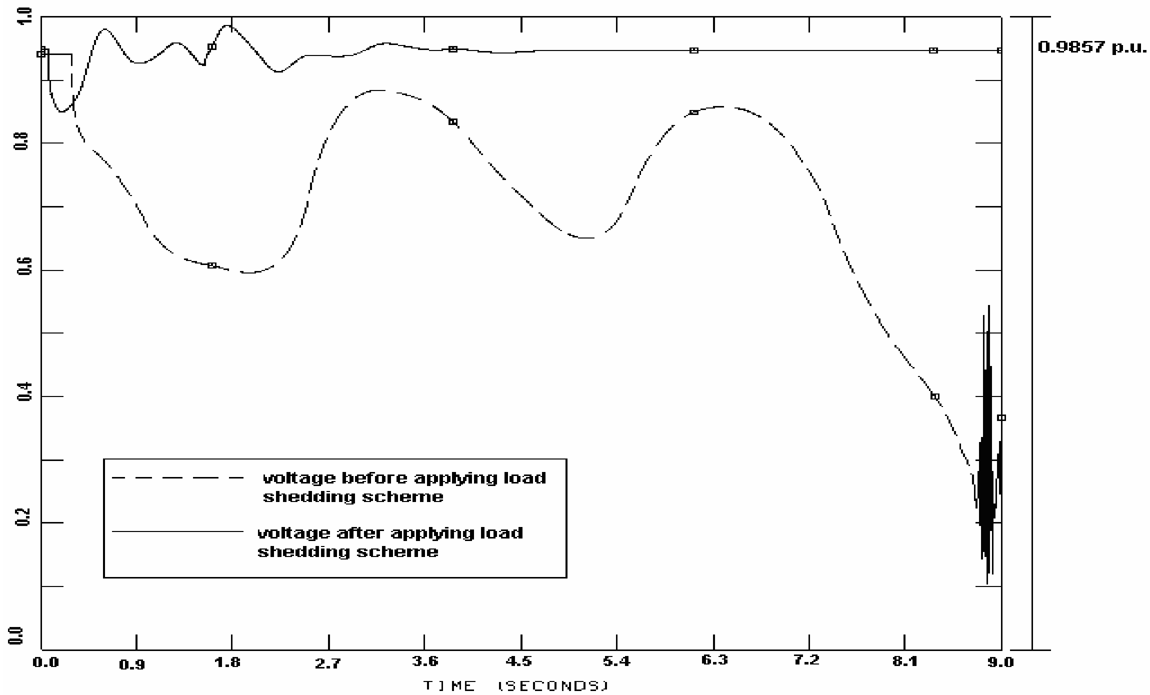

Fig. 11 IEEE 39 bus system Unacceptable case: Voltage at bus 7 when generator 32 is lost (before and after applying load shedding)

The figure 11 shows the voltage at bus 7 before and after implementing load shedding scheme when generator at bus 32 is lost. After applying load shedding the voltage profile is improved very much. It settles to a value of 0.9857 p.u. Similarly the other cases have also shown improved voltages. In the following section, one of the cases is discussed and the results are plotted. The frequency plot without load shedding and voltage plots with and without load shedding are shown in the figures 12-14. After load shedding has been applied, the voltage profile improves. Also, the frequency of the system shows improvement as seen in figure 13. It reaches a value of 59.99 Hz.

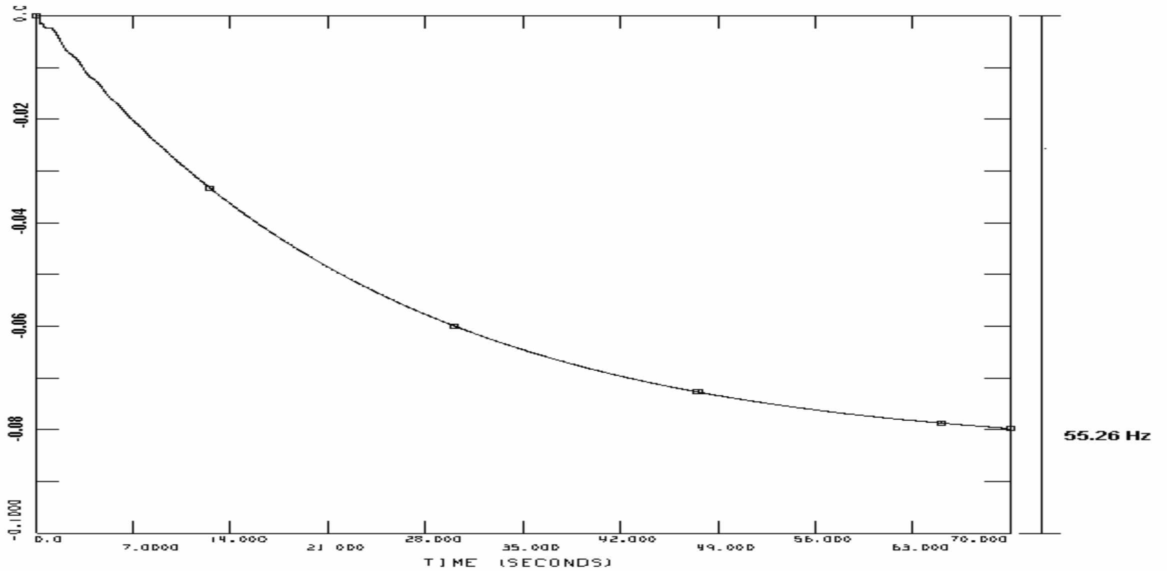

Fig. 12 IEEE 39 bus system acceptable case: Frequency when generator 34 is lost

(without load shedding)

Figure 12 represents the frequency plot after a disturbance has occurred before implementing the load shedding scheme. As can be seen the disturbance causes the frequency to settle at a value much lower than the acceptable value.

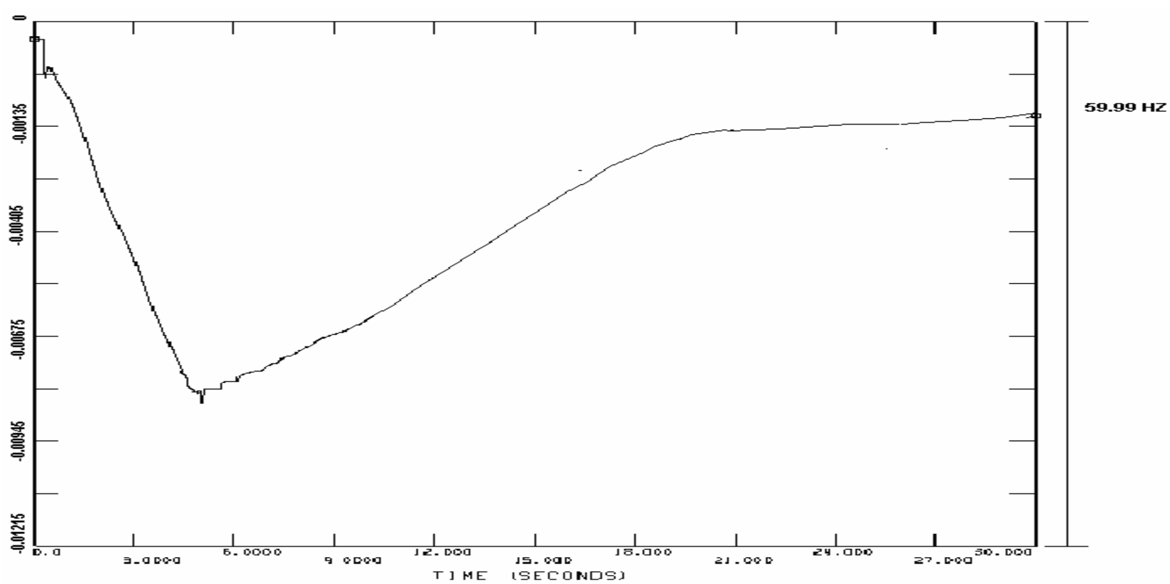

Fig.13 IEEE 39 bus system acceptable case : Frequency when generator 34 is lost

(applying load shedding)

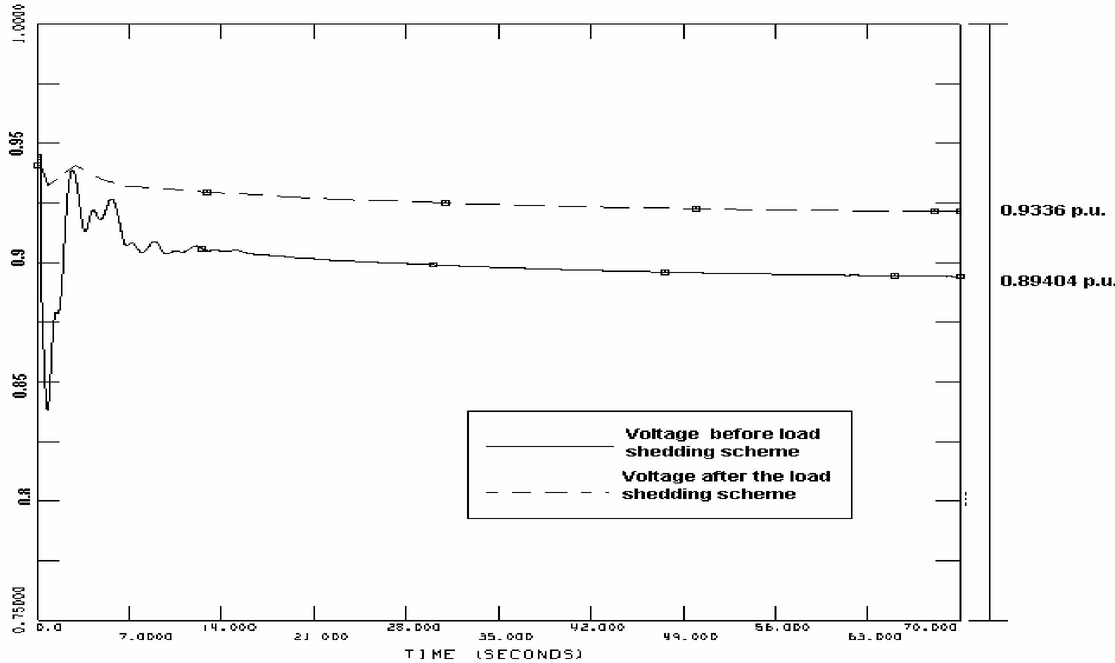

Fig. 14 IEEE 39 bus system acceptable case : Voltage at bus 7 when generator34 is lost (before and after load shedding)

The voltage in the above case, as shown in figure 14, improves from 0.894 p.u. before load shedding to a value of 0.933 p.u. after applying the load shedding scheme. Similarly the frequency has also shown an improvement.

Case study 2: Loss of a generator for the IEEE 145 bus system

The IEEE 145 bus test system has also been tested with the algorithm. Ten test cases in this situation are taken. The generators shed in this case are generators 95, 98, 110, 122, 104, 117, 118, 143, 135 and 144. The generation power lost due to the loss of each of the above generators is given in the table10.

TABLE 10: MW generation lost for loss of a generator (IEEE 145 bus system)

Generator lost	MW generation lost
95	131
98	426
110	700
122	1009
104	2000
117	2627
118	4220
143	5254
135	5982
144	11397

Based on the estimated disturbance the load shed at each load bus is calculated and tabulated for all the 10 cases in the tables 11-12.

TABLE 11: Load shed at each bus for test cases 1-5 (IEEE 145 bus system)

Bus no.	Gen 67	Gen 89	Gen 95	Gen 115	Gen 118
	(1486 MW)	(673MW)	(131 MW)	(2493 MW)	(4220 MW)
34	11.69	5.31	1.03	19.6	33.19
35	11.69	5.31	1.03	19.6	33.19
51	38.96	17.68	3.42	58.45	58.45
58	23.38	10.61	2.05	46.1	76.3
66	38.96	17.68	3.42	65.34	102.2
74	11.69	5.31	1.03	19.6	81.9
78	89	47.61	9.21	89	89
80	17.1	17.1	14	17.1	17.1
81	82.2	82.2	22.8	82.2	82.2
88	69	69	19	69	69
93	100.4	100.4	1.71	100.4	100.4
102	37.6	37.6	2.03	37.6	37.6
104	30.2	19.21	3.42	30.2	30.2
105	96	14.15	2.74	96	96
106	64	17.68	3.42	64	64
110	100.4	11.79	2.28	100.4	100.4
111	60.4	15.92	3.08	60.4	60.4
115	238.05	14.15	2.74	683.5	683.5
116	11.69	5.31	1.03	240.76	792.6
117	23.51	10.67	2.06	39.43	485.3
118	16.23	7.37	1.43	27.23	235.43
119	6.75	3.07	0.59	11.33	19.17
121	24.61	11.17	2.16	41.27	69.87
124	14.61	6.63	1.28	24.5	41.48
128	38.96	17.68	3.42	65.34	110.62
130	27.27	12.38	2.39	45.74	77.45
131	7.79	3.54	0.68	13.07	22.12
132	23.43	10.63	2.06	39.29	66.52
134	15.58	7.07	1.37	26.14	44.25
135	7.79	3.54	0.68	13.07	22.12
136	12.17	5.53	1.07	20.42	34.57
137	23.38	10.61	2.05	39.21	66.38
139	7.79	3.54	0.68	13.07	22.12
140	24.35	11.05	2.14	40.84	69.14
TOTAL	**1486**	**674.5**	**130.47**	**2492.32**	**4219.58**

TABLE 12: Load shed at each bus for test cases 6-10 (IEEE 145 bus system)

Bus no.	Gen 119	Gen 137	Gen 134	Gen 141	Gen 139
	(8954 MW)	**(12068 MW)**	**(20626 MW)**	**(37911MW)**	**(56834 MW)**
34	45.05	45.05	45.05	45.05	45.05
35	49.19	49.19	49.19	49.19	49.19
51	58.45	58.45	58.45	58.45	58.45
58	76.3	76.3	76.3	76.3	76.3
66	102.2	102.2	102.2	102.2	102.2
74	81.9	81.9	81.9	81.9	81.9
78	89	89	89	89	89
80	17.1	17.1	17.1	17.1	17.1
81	82.2	82.2	82.2	82.2	82.2
88	69	69	69	69	69
93	100.4	100.4	100.4	100.4	100.4
102	37.6	37.6	37.6	37.6	37.6
104	30.2	30.2	30.2	30.2	30.2
105	96	96	96	96	96
106	64	64	64	64	64
110	100.4	100.4	100.4	100.4	100.4
111	60.4	60.4	60.4	60.4	60.4
115	683.5	683.5	683.5	683.5	683.5
116	792.6	792.6	792.6	792.6	792.6
117	485.3	485.3	485.3	485.3	485.3
118	651.9	651.9	651.9	651.9	651.9
119	2094	2094	2094	2094	2094
128	1375.72	4011.4	4075	4075	4075
130	164.33	221.52	4328	4328	4328
131	46.95	63.28	3333.36	18364.49	21840
132	141.15	190.27	325.16	491.9	491.9
137	140.85	189.86	324.46	596.38	894.03
139	46.95	63.28	108.15	198.79	298
140	146.71	197.76	337.96	621.21	931.24
144	102.7	138.44	236.59	434.87	651.9
145	234.74	316.42	540.74	993.93	1489.99
TOTAL	**8953.62**	**12069.3**	**20625.8**	**37912.2**	**56833.4**

The load shedding scheme is employed to obtain favorable results. As observed with the IEEE 39 bus system, the IEEE 145 bus system also has certain cases which result in unacceptable voltage and frequency values after experiencing disturbances. In one such case, the voltage is observed before and after the load shedding is applied. This plot is presented in figure 15. The frequency at which the system becomes unstable is 54.76 Hz.

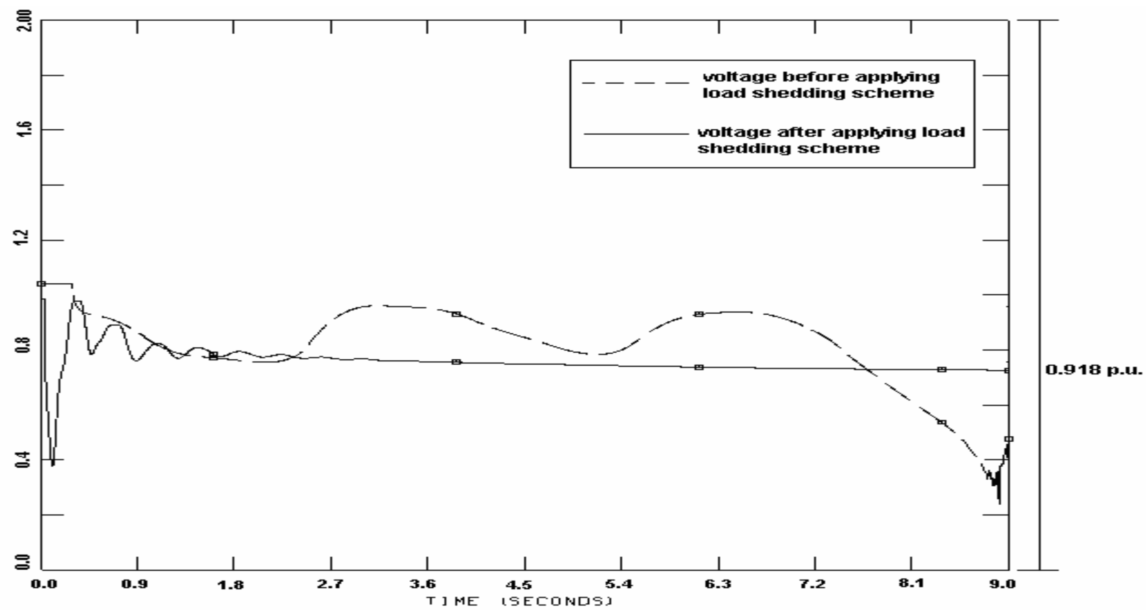

Fig.15 IEEE 145 bus system unacceptable case: Voltage at bus 7 (before and after applying load shedding)

After applying the load shedding scheme an improvement in the voltage is observed. Similarly the frequency experiences a gradual improvement. This is seen in figure 21.

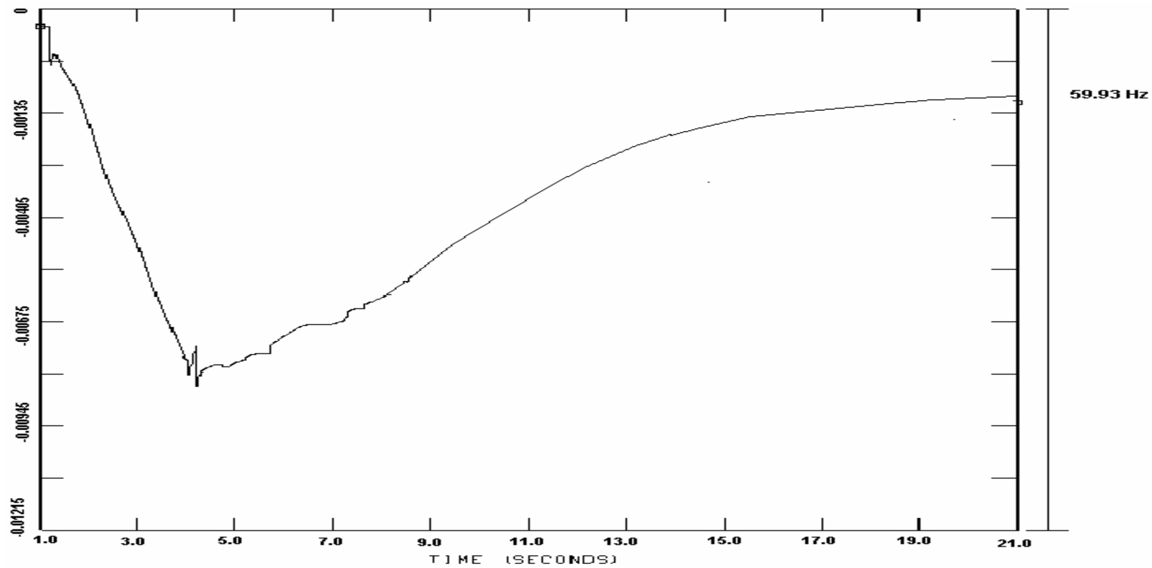

Fig. 16 IEEE 145 bus system unacceptable case : Frequency with load shedding

When load shedding is applied at 4.0 secs, there is a spike in the frequency and then gradually it rises above the 59.7 Hz mark by the end of the ninth second. Thus it reaches a value of 59.93 Hz by the end of 21 seconds.

Similarly for another case, we have the following voltage and frequency observation. After load shedding has been applied an improvement in the frequency plot is observed since the frequency starts rising above 59.7 Hz in about 7.68 seconds. In totality, it takes around 22.34 seconds for the system to reach an acceptable value of 59.93 Hz. The corrected voltage and frequency plots are in figures 17 and 18.

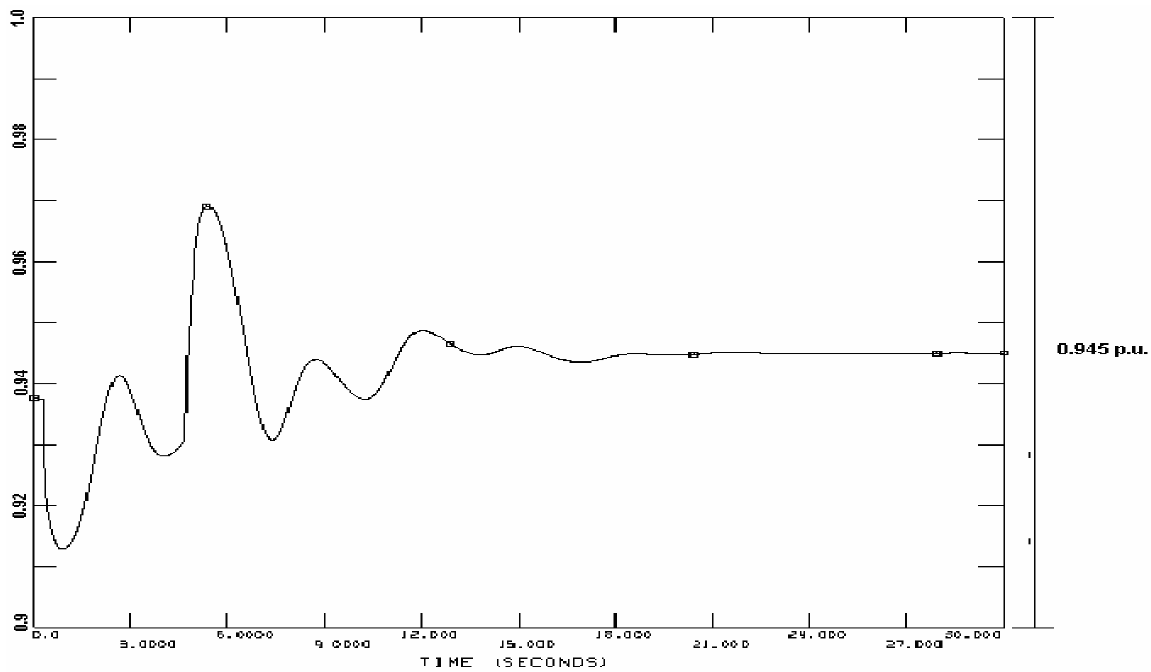

Fig.17 IEEE 145 bus system acceptable case : Voltage at bus 7 with load shedding

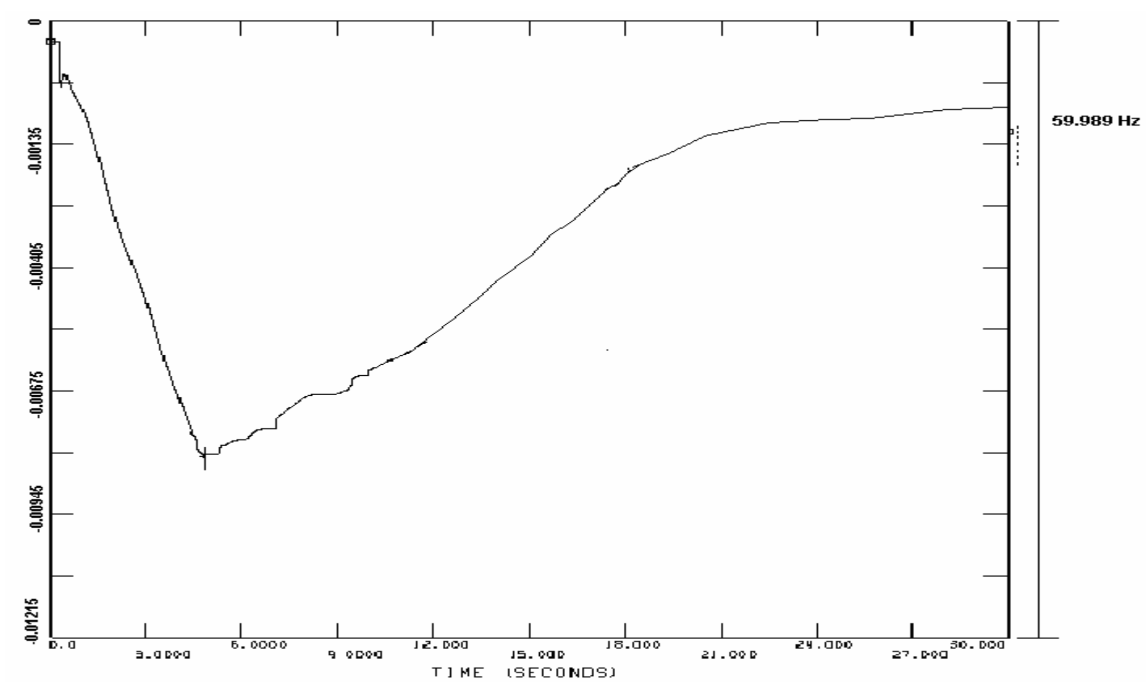

Fig. 18 IEEE 145 bus system acceptable case : Frequency with load shedding

Overall, the load shedding scheme has prevented the system from bordering over into unstable region. In cases where the system was stable but frequency and voltage were below the desired values, load shedding has helped improve both these parameters to suit the limits which have been pre set for them. Thus the load shedding scheme has shown sufficient, desirable and acceptable improvements in the frequency and voltage values.

Case Study 3: Loss of a transmission line

The third case study considers the loss of a transmission line. The study system in consideration is once again the IEEE 39 bus system. The transmission lines of this system can be ranked based on how critical they are to the system. Certain lines connecting the generator buses to the rest of the system are the most critical since their loss results in the loss of the entire generator and is equivalent to the studies made in the previous two sections. The most critical line in this system is the line 16-19. The loss of this line forms two islands, separating the generators at buses 33 and 34 from the rest of the system. The island with the remaining generators become unstable since the load requirement in that area is much higher than the generated power. This is true since the island with the two generators at bus 33 and 34 have very little load in that island. The critical transmission lines are ranked according to the severity of the disturbance caused due to their loss. The table 13 ranks the critical branches based on the generators they isolated from the rest of the system.

TABLE 13: MW generation lost due to a transmission line loss

From bus	To bus	Generation capacity lost (MW)
16	19	1140
2	30	250
6	31	560
10	32	650
19	33	632
20	34	508
22	35	650
23	36	560
25	37	540
29	38	830
9	39	1000

These lines, as shown in the above table, when tripped cause the system to behave similarly to the situations when generators are lost. The only additional disturbance is the line 16-19 which causes two generators to be isolated separately from the system. The table 13 shows the transmission lines which are directly connected to generators. The next set of lines are close to the generators but by tripping them the generators are not isolated from the rest of the system. These lines when tripped cause disturbance to the system which leads to the decline of the system frequency. One such line, 22-23, is tripped. Without applying the load shedding scheme the voltage at one of the buses, bus 7, is shown in fig 19 below. The frequency plot after tripping the line is shown below in figure 20.

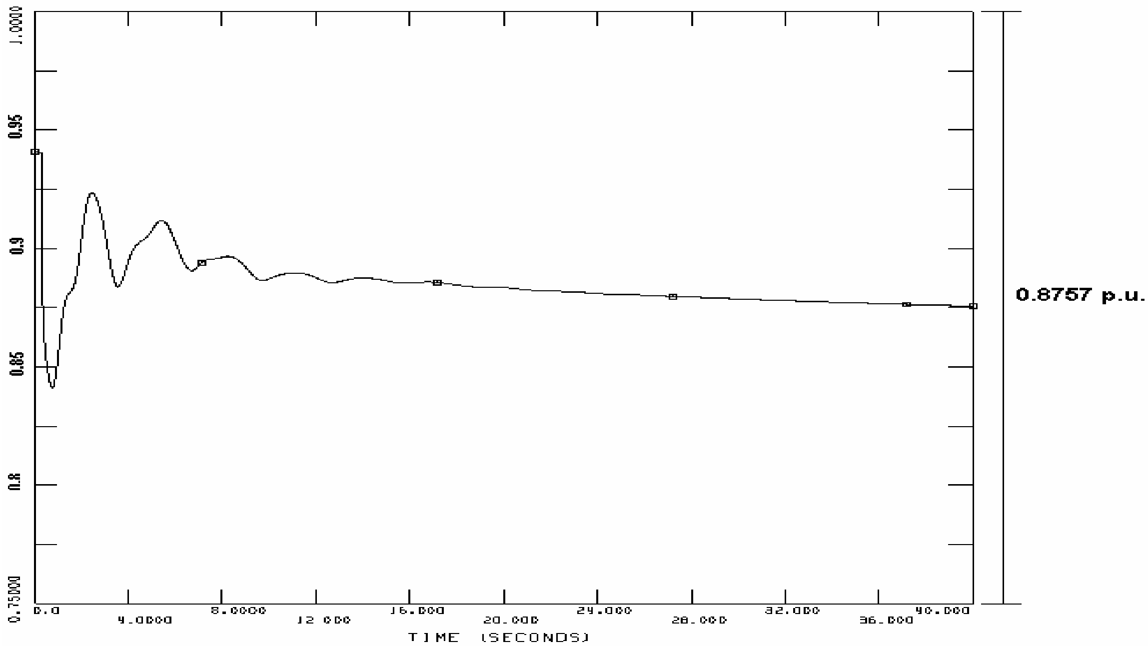

Fig.19 IEEE 39 bus system : Voltage at bus 7 due to the tripping of line 16-19

(without load shedding)

The voltage is definitely lower than the acceptable value. Similarly a frequency decline is observed which is due to the isolation of the generators 33 and 34 from the rest of the system.

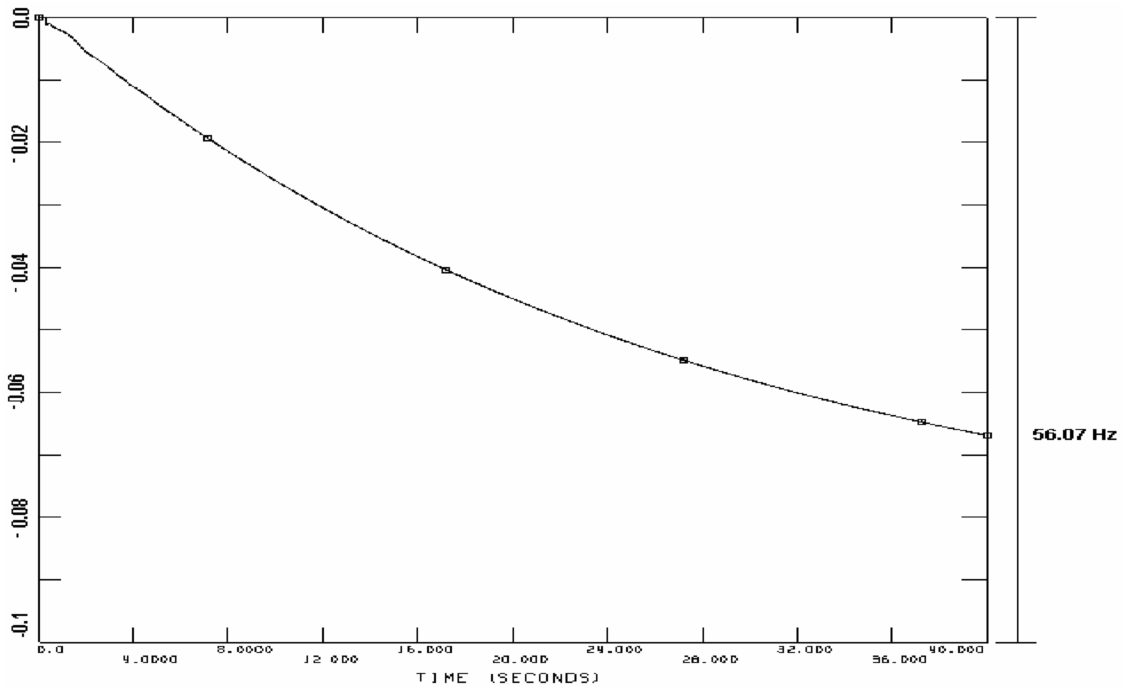

Fig.20 IEEE 39 bus system : Frequency due to the tripping of line 16-19

(without load shedding)

The frequency decreases below the lower limit. The rate of change of frequency plot provides the input data to estimate the disturbance magnitude. Thus the estimated disturbance from the rate of change of frequency plot is 557 MW. On applying the load shedding scheme the frequency plot obtained is shown below in fig 21. The final frequency stabilizes at a value of 59.912 Hz.

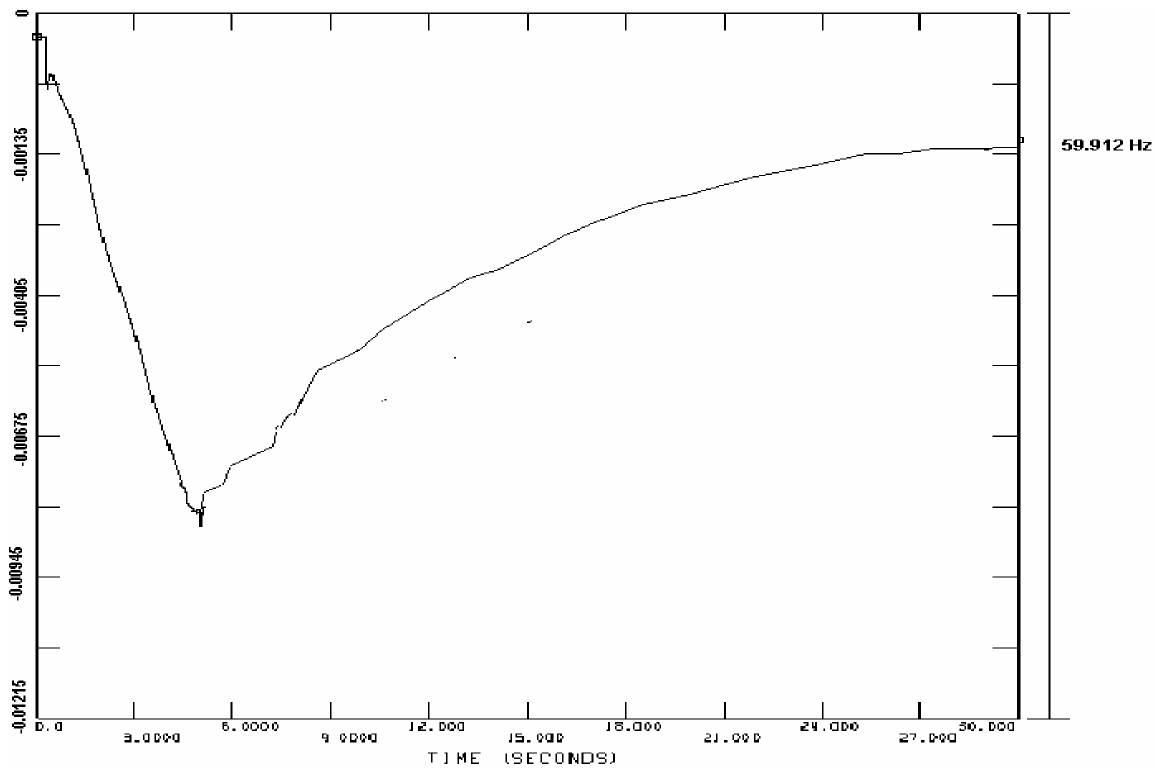

Fig.21 IEEE 39 bus system : Frequency plot after tripping line 16-19

(applying load shedding)

The other transmission lines when tripped cause a disturbance which decreases the frequency but still maintains it above the threshold value required to initiate the load shedding scheme. In such cases the frequency reaches a low value of around 59.89 Hz. In this case the load shedding scheme will not be initiated. Except for the critical buses shown above the loss of other transmission lines may not cause severe decline of frequency although in certain it causes a decrease in the voltage at certain buses.

Duke Energy System : Generator Loss

Duke Energy provided a system, the data for which was obtained from their simulator. The power system simulations have been carried out in AREVA's E-Terra, an offline software system. This system simulates the environment favorable for training electrical power system dispatchers. This simulator uses the dynamic power system model which consists of details like the system topology, equipments and real time conditions. Various real time operations such as checking the relay operations, frequency and generation variations and control center functions such as Automatic Generation Control are simulated using this software. It also provides tools for the instructor for training the control center trainees. The replay mode provided in this simulator can recreate real time disturbance conditions for analysis. Also operator actions can be replayed so that the trainees can observe the effect of taking certain actions on the system.

A disturbance has been simulated in which the generating units at one of the buses were tripped and the frequency plots are observed before and after implementing the proposed load shedding scheme. The equivalent of the Duke Energy system consists of ninety seven buses. There are fifty three generators in the system. This equivalent system is subjected to the loss of a generating unit at the McGuire bus. Due to this disturbance, the system frequency and voltage start declining and the load shedding scheme has to be employed in order to get it back to its normal operating conditions. The resultant voltage and frequency plots are presented in the following chapter.

The system provided by Duke Energy is subjected to the loss of a generator. The average system frequency and the bus voltages decline to an unacceptable value. In order to improve the frequency and the voltage profile, the proposed load shedding scheme is implemented. The voltage and frequency plots show substantial improvements after employing the load shedding scheme. The load shed at each of the buses is presented in table 14. This amount is calculated using the proposed load shedding scheme. The two generator units at McGuire are tripped and the disturbance simulation has been created. These units were supplying 1151.34 MW and 1181.33 MW respectively.

TABLE 14: Load shed at each bus for the Duke Energy System

Bus Name	Load shed at each bus	Bus Name	Load shed at each bus
McGuire	36.61	Peach Valley	9.83
McGuire	42.74	Parkwood	27.5
Jocassee	28.17	Parkwood	19.04
Jocassee	43.65	Ripp	2.18
Pleasant garden 525KV	5.07	Rural Hall	19.16
Anderson	44.49	Rural Hall	16.49
Allen	30.6	Riverbend	49.36
Allen	22.48	Riverbend	11.21
Beckerdite	4.76	Shelby	4.11
Beckerdite	66.44	Shelby	5.33
Belews Creek	8.74	Shady Grove	28.71
Buck	53.51	Shady Grove	0.55
Buck	46.15	Shiloh	20.92
Central	13.44	Stamey	51.08
Central	20.89	Stamey	52.42
Cliffside	32.28	Tiger	9.59
Cliffside	83.87	Tiger	23.35
Catawba	31.92	Winecoff	38.34
E Durham	26.64	Winecoff	5.58
E Durham	0	Woodlawn	31.94
Eno	29.15	Woodlawn	18.82
Eno	33.94	E Spartanburg	0.09

TABLE 15: Load shed at each bus for Duke energy system (contd)

Bus Name	Load shed at each bus	Bus Name	Load shed at each bus
Harrisburg	22.1	Fishing Creek	64
Harrisburg	16.91	Fairview	9.92
Lincolnton	26.86	Great Falls	53.81
Longview	21.65	Greensboro	15.85
Longview	30.66	Greenville	38.14
Lakewood	5.37	Hodges	35.06
Mitchell River	63.01	Hickory	22.66
Mitchell River	25.08	Horseshoe	17.22
Marshall	17.97	Hilltop	16.31
N Greensboro	14.99	Hendersonville	3.21
N Greensboro	17.71	Longview	16.95
N Greenville	22.38	Lancaster	13.42
N Greenville	3.72	Lookout	15.82
Oakboro	5.47	Lee	42.97
Oakboro	38.2	Morning Star	82.72
Oconee	41.53	Miller Hill	35.11
Oconee	3.94	Morris	4.28
Pacolet	1.53	McDowell	29.21
Pacolet	4.93	Monroe	27.18
Peacock	57.27	N Charlotte	0.11
Peacock	10.12	Oxford Hydro	0
Pisgah	22.55	Poplar	30.12
Pisgah	44.25	Toxaway	44.18
Peach Valley	15.75		

The load shed at each bus is represented in table 14 and the load limits are taken into consideration while calculating the load shed at each bus. Figure 22 shows the frequency plot after applying the load shedding scheme.

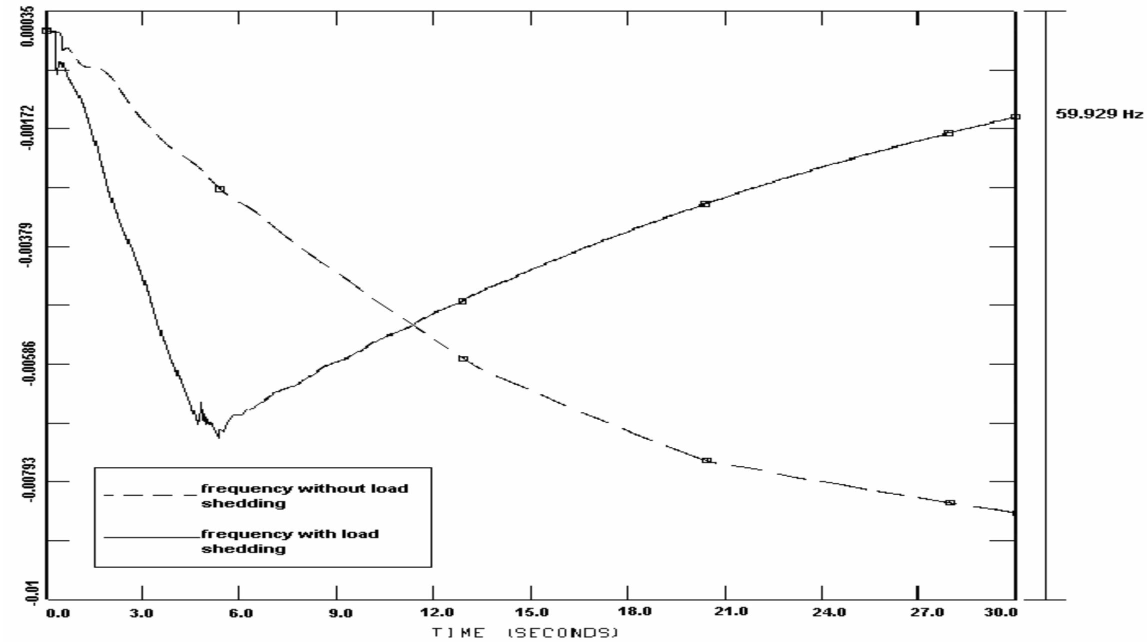

Fig.22 Frequency of the Duke Energy System with and without load shedding

The frequency initially undergoes a decline as soon as the disturbance is applied to the system. As the frequency decreases below 59.7 Hz the load shedding scheme is implemented such that the frequency starts increasing as the load is shed from each bus. Finally, the frequency plot settles at a value of 59.929 Hz.

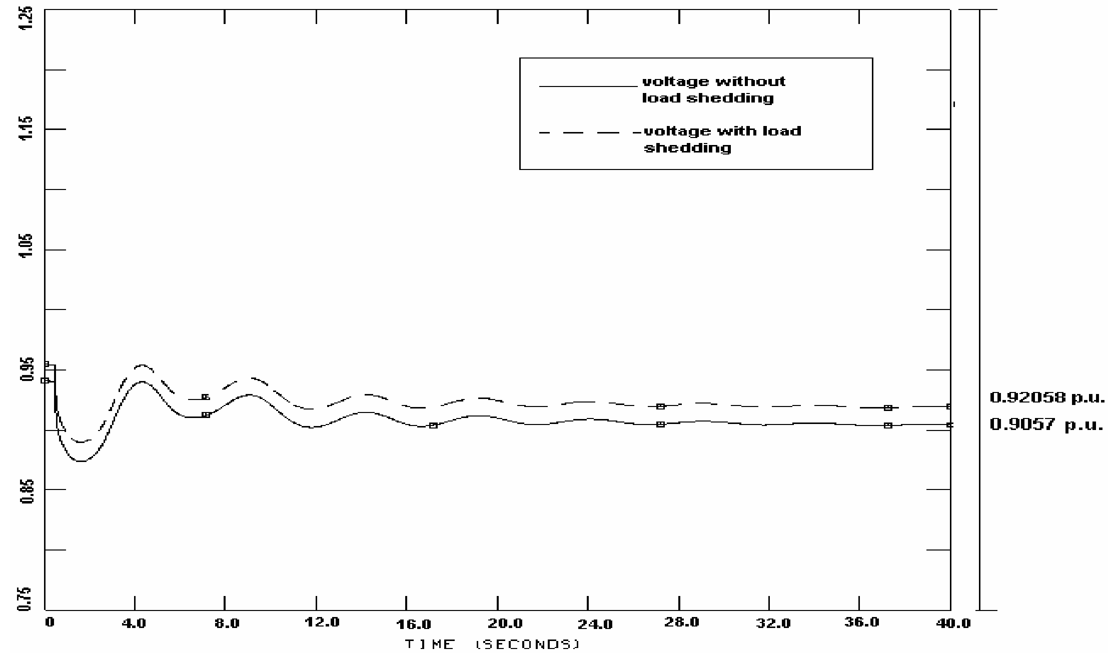

Fig.23 Voltage profile at Allen (duke energy system bus) with and without load shedding

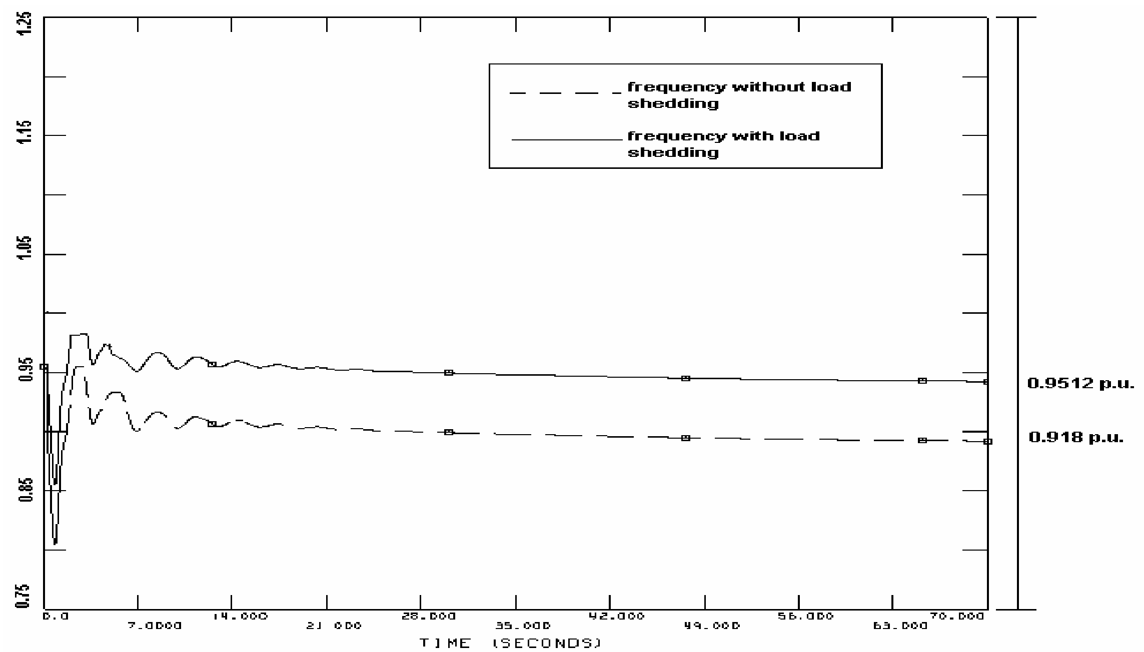

Fig.24 Voltage profile at Catawba (duke energy system bus) with and without load shedding.

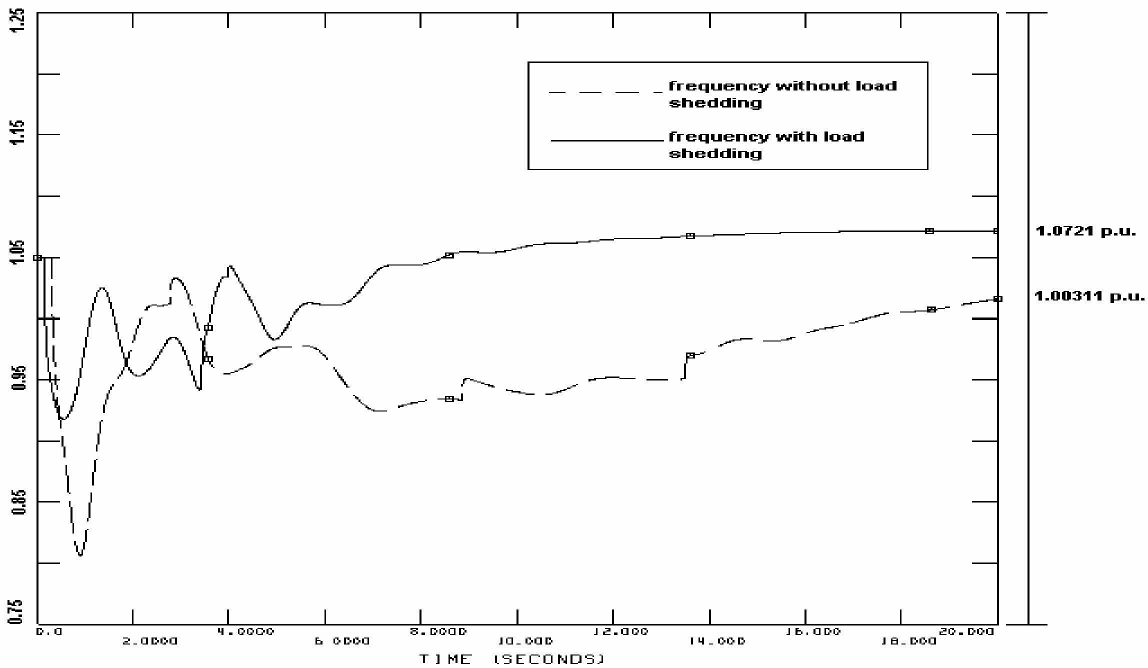

Fig.25 Voltage profile at Shiloh (duke energy system bus) with and without load shedding.

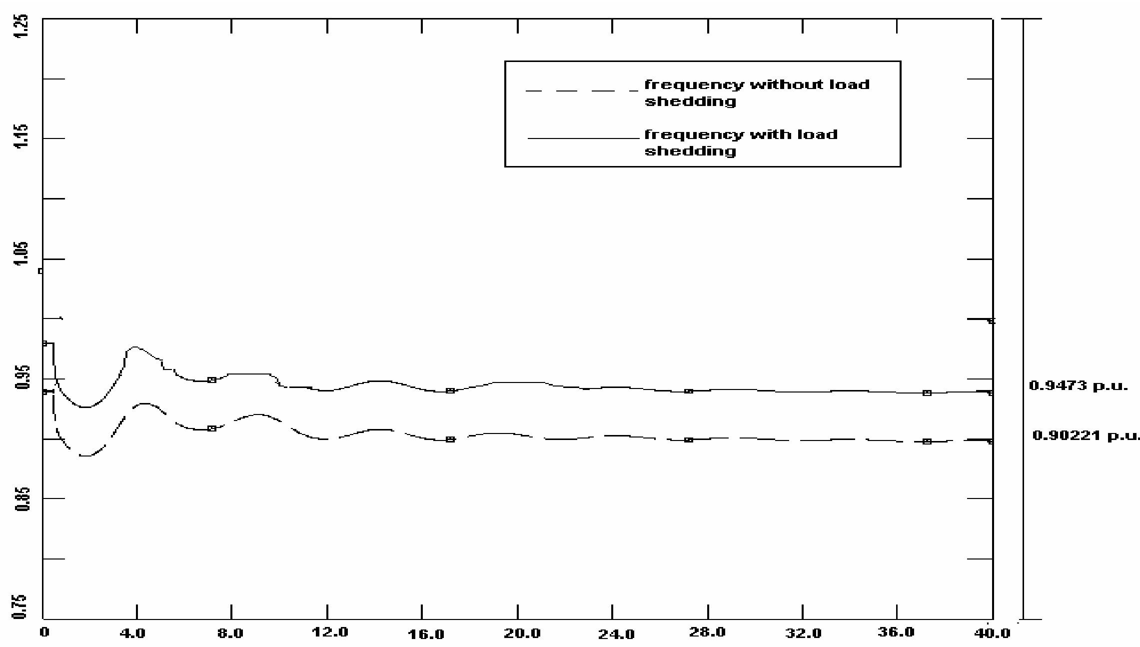

Fig.26 Voltage profile at Marshall (duke energy system bus) with and without load shedding.

The voltage profile at the bus situated in Allen is shown in figure 23 as it is one of the critical voltages. The voltage value before applying the load shedding scheme is 0.9057 p.u. and the one after applying the load shedding scheme is 0.92058 p.u.. On comparing the two graphs in figure 23 shows that the load shedding scheme improves the voltage value. Similarly the voltage profiles at Catawba, Shiloh and Marshall are shown in figures 24, 25 and 26 which are with and without load shedding.

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

Conclusion

Load shedding schemes are initiated in order to relieve system overload and correct the declining system frequency. This thesis is focussed on a load shedding scheme which not only corrects the system frequency but also improves the voltage profile through out any system. The main purpose of this method is that it considers the rate of change of frequency and the voltage sensitivities before implementing the actual load shedding scheme. The scheme is simple and does not involve complicated calculations. It has proved to be successful in restoring the frequency within its pre-defined limits. It has also improved the voltage profile at certain buses which had critically low voltage before load shedding was applied.

The conventional load shedding schemes reviewed in chapter 2 were a strong basis for developing the proposed scheme. They provided details of the schemes which are already in practice in the industry as well as the schemes which are still being tested on a research level. The proposed scheme has been an effort to make improvements on some of the drawbacks of the existing schemes by considering the frequency and voltage as input variables for deciding the amount of load to be shed.

Based on the observations and results obtained for the above test cases, it can be said that shedding the load based on the voltage sensitivities definitely improves the frequency and voltage plots. The load shedding algorithm is triggered off at the pick up frequency of 59.7 Hz for a 60 Hz system. The case studies give satisfactory improvements in the frequency plot. This frequency is restored within its upper and lower limits within 20 seconds. There have been several cases considered here. Two of these have been cases in which the system is unable to provide sufficient load power after the loss of generators at bus 32 and 33. As a result of this the bus voltages decrease to a very low value. These are considered as special cases. Besides these cases, there are other cases in which the frequency and voltage settle at low values which are unacceptable. By implementing load shedding in these cases the system aims to improve the frequency and voltage profile. The input measurement of the rate of change of the frequency data is quite accurate. As a result, the disturbance magnitude evaluated in these cases has also been significantly close to the actual loss of the generation.

In this situation the load shedding scheme begins operation within 0.3 seconds and the frequency improves drastically so that the system does not enter the unstable region. The practical systems might have a propagation delay differing from the simulated values. In other cases, although the system settles down after a disturbance, its frequency and voltage profiles are below the accepted standards. In these cases the load shedding scheme improves these two parameter values within the acceptable limits. On an average, after the load shedding is applied the frequency rises above 59.7 Hz in about 7 seconds in the above cases. Also, it takes approximately 20 seconds to attain a value of 59.9 Hz from the time of load shedding.

In the third case study transmission lines are tripped. The lines which directly connect the generators to the rest of the system are the critical lines. If a generator has just one transmission line connecting it to the system, this becomes a crucial line as its loss will isolate the generator from the system. But in case the generator is connected to the system via two lines, then the loss of one will cause overloading of the other transmission line. This is seen in case of the generator at bus 39 since it generates a large capacity of more than 1000 MW. Thus the transmission line limits need to be taken into account. When these critical lines are removed the load shedding procedure applied is similar to when there is a loss of a generator.

The proposed scheme has been tested on the equivalent system provided by Duke Energy. The disturbance is created by tripping units at the McGuire bus and observing the changes in the system. As a result of this, the frequency starts declining and the voltage at certain critical buses decreases. On testing the load shedding scheme, improvements in the frequency and voltage are observed. The frequency which initially declined to a low value increases and settles to a value of 59.929 Hz. Similarly, the voltage profile shows an increase after implementing the load shedding scheme.

The formula based on voltage sensitivities gives good results. The amount of load shed from each bus is less and there is flexibility in the number of steps in which load is shed. The load at each bus is shed in one step, but this can be further divided into more number of steps as per requirements. Hence, there is no sudden change in load. Thus this makes the algorithm much more flexible. Over shedding is avoided and there is a smooth improvement in the system frequency.

Future work

There is a definite scope for improving the results by fine tuning the algorithm. Economical considerations need to be considered before shedding the load since certain loads cannot be kept offline. Also depending on the current market conditions the prices might vary. This needs to be kept in mind before initializing the load shedding scheme.

Regular, hourly updates about the load are necessary to make an accurate and optimal load shedding scheme. Besides this a multiple contingency scenario considering the loss of a generator along with the loss of a transmission line would create a critical situation. The study and testing of the scheme in such a case is something which can be worked on in the future.

With the advent of modern technology, synchrophasors have started carving a niche for themselves in the wide area monitoring and protection area. Briefly stated , a synchrophasor is defined as a phasor calculated from data samples using a standard time signal as the reference for the measurement [44]. Synchronized phasors from remote sites have a defined common phase relationship. So far, synchrophasors have been used in determining Voltage stability indices, used in protective relays, for determining wide area angle stability and also used to check for black starting abilities of generators. One possible modification to the existing research would be collecting real time synchrophasor data and employing the proposed algorithm using this. Shown above were some of the possibilities which widen the scope for future research. Thus further analysis and developments are possible with the existing scheme which will enhance it to provide much more accurate and efficient results.

APPENDICIES

Appendix A

Code for the Load Shedding Scheme

```
%LOAD SHEDDING ALGORITHM%
%-----------------------------------------%

%Collection of data for calculation of magnitude of disturbance

%Inertia Constants of all the generators
inertia=xlsread('inertia_constants');

%Equivalent inertia constant
H=inertia_sum(inertia)-lost_inertia(gen_lost);

%df/dt at due to the disturbance
df_dt=xlsread('dfbydt');
dfdt_final=average(df_dt);

%Magnitude of disturbance in MW
Pdiff=(dfdt_final*2*H/60)*1000;
disp('The magnitude of the disturbance is: ');
disp(Pdiff);

%Voltage, admittance, delta and theta values (considering load buses only)
V=xlsread('voltage');
[load_bus,a]=size(V);

Y=xlsread('Yload_bus');
delta=xlsread('delta');
theta=xlsread('theta');
load=xlsread('load_present');

%Calculate the dQ/dV value at each load bus
for m=1:load_bus
   dqbydv(m)=0;
    for n=1:load_bus
        if (n~=m)
            dq_dv=V(n)*Y(m,n)*sin((delta(m)-delta(n))-(theta(m)-theta(n)));
            dqbydv(m)=dqbydv(m)+dq_dv;
        end
    end
end
```

```
% Calculate the dV/dQ and the summation of dV/dQ
for m=1:load_bus
   dvbydq(m)=(1/dqbydv(m));
end

sum=0;
for m=1:load_bus
   sum=sum+dvbydq(m);
end

%Calculate load at each bus
for m=1:load_bus
   excess(m)=0; % vector used when load at a bus is less than the estimated load to be
shed
end

for p=1:load_bus
   loadshed(p)=(dvbydq(p)/sum)*Pdiff;
   if p~=1
      loadshed(p)=loadshed(p)+excess(p-1);
   end

   if loadshed(p)>load(p)
      excess(p)=loadshed(p)-load(p);
      loadshed(p)=load(p);
   end
end

%Output of the load to be shed at each bus
wk1write('loadshed',loadshed);
```

Appendix B

IEEE System Data

The generator parameters for the IEEE 39 bus system

Unit No.	H	R_a	x'_d	x'_q	x_d	x_q	T'_{do}	T'_{qo}	x_l
1	500.0	0	0.006	0.008	0.02	0.019	7.0	0.7	0.003
2	30.3	0	0.0697	0.170	0.295	0.282	6.56	1.5	0.035
3	35.8	0	0.0531	0.0876	0.2495	0.237	5.7	1.5	0.0304
4	28.6	0	0.0436	0.166	0.262	0.258	5.69	1.5	0.0295
5	26.0	0	0.132	0.166	0.67	0.62	5.4	0.44	0.054
6	34.8	0	0.05	0.0814	0.254	0.241	7.3	0.4	0.0224
7	26.4	0	0.049	0.186	0.295	0.292	5.66	1.5	0.0322
8	24.3	0	0.057	0.0911	0.290	0.280	6.7	0.41	0.028
9	34.5	0	0.057	0.0587	0.2106	0.205	4.79	1.96	0.0298
10	42.0	0	0.031	0.008	0.1	0.069	10.2	0.0	0.0125

The network data for the system consists of line data and transformer data.

Line Data					Transformer Tap	
From Bus	To Bus	R	X	B	Magnitude	Angle
1	2	0.0035	0.0411	0.6987	0.000	0.00
1	39	0.0010	0.0250	0.7500	0.000	0.00
2	3	0.0013	0.0151	0.2572	0.000	0.00
2	25	0.0070	0.0086	0.1460	0.000	0.00
3	4	0.0013	0.0213	0.2214	0.000	0.00
3	18	0.0011	0.0133	0.2138	0.000	0.00
4	5	0.0008	0.0128	0.1342	0.000	0.00

4	14	0.0008	0.0129	0.1382	0.000	0.00
5	6	0.0002	0.0026	0.0434	0.000	0.00
5	8	0.0008	0.0112	0.1476	0.000	0.00
6	7	0.0006	0.0092	0.1130	0.000	0.00

Line Data					Transformer Tap	
From Bus	To Bus	R	X	B	Magnitude	Angle
6	11	0.0007	0.0082	0.1389	0.000	0.00
7	8	0.0004	0.0046	0.0780	0.000	0.00
8	9	0.0023	0.0363	0.3804	0.000	0.00
9	39	0.0010	0.0250	1.2000	0.000	0.00
10	11	0.0004	0.0043	0.0729	0.000	0.00
10	13	0.0004	0.0043	0.0729	0.000	0.00
13	14	0.0009	0.0101	0.1723	0.000	0.00
14	15	0.0018	0.0217	0.3660	0.000	0.00
15	16	0.0009	0.0094	0.1710	0.000	0.00
16	17	0.0007	0.0089	0.1342	0.000	0.00
16	19	0.0016	0.0195	0.3040	0.000	0.00
16	21	0.0008	0.0135	0.2548	0.000	0.00
16	24	0.0003	0.0059	0.0680	0.000	0.00
17	18	0.0007	0.0082	0.1319	0.000	0.00
17	27	0.0013	0.0173	0.3216	0.000	0.00
21	22	0.0008	0.0140	0.2565	0.000	0.00
22	23	0.0006	0.0096	0.1846	0.000	0.00
23	24	0.0022	0.0350	0.3610	0.000	0.00
25	26	0.0032	0.0323	0.5130	0.000	0.00
26	27	0.0014	0.0147	0.2396	0.000	0.00
26	28	0.0043	0.0474	0.7802	0.000	0.00
26	29	0.0057	0.0625	1.0290	0.000	0.00
28	29	0.0014	0.0151	0.2490	0.000	0.00
12	11	0.0016	0.0435	0.0000	1.006	0.00
12	13	0.0016	0.0435	0.0000	1.006	0.00
6	31	0.0000	0.0250	0.0000	1.070	0.00

10	32	0.0000	0.0200	0.0000	1.070	0.00
19	33	0.0007	0.0142	0.0000	1.070	0.00
20	34	0.0009	0.0180	0.0000	1.009	0.00
22	35	0.0000	0.0143	0.0000	1.025	0.00
23	36	0.0005	0.0272	0.0000	1.000	0.00
25	37	0.0006	0.0232	0.0000	1.025	0.00
2	30	0.0000	0.0181	0.0000	1.025	0.00

REFERENCES

[1] P.M Anderson, A.A. Fouad, (2003) Power System Control and Stability, IEEE series on Power Engineering, John Wiley and Sons, Second Edition.

[2] P. Kundur, (1994) Power System Stability and Control, Electric Power Research Institute-Power System Engineering series, McGraw-Hill.

[3] William D. Stevenson Jr., (1982) Elements of Power System Analysis, Electrical & Electronic Engineering Series, Mc-Graw-Hill, Fourth Edition.

[4] C.W. Taylor, (1993) Power System Voltage Stability, Electric Power Research Institute-Power System Engineering series, McGraw-Hill.

[5] FERC standards, Electric Reliability, http://www.ferc.gov/industries/electric/indusact/reliability/standards.asp#skipnavsub

[6] Florida Reliability Coordinating Council, (2001) FRCC standards handbook.

[7] California ISO, Emergency Load Shedding scheme.

[8] Mid Atlantic Area Control, MAAC Under Frequency Load Shedding Program Requirements.

[9] Jeff Mechenbier, Dr. Abraham Ellis, Richard Curtner, Dr. Satish Ranade, Design of under voltage load shedding scheme.

[10] South West power Pool, SPP Criteria for Load Shedding.

[11] A.A Mohd Zin, H. Mohd Hafiz, M.S. Aziz, (2001) A Review of Under frequency Load Shedding scheme on TNB system.

[12] Hamish H. Wong, Joaquin Flores, Ying Fang, Rogelio P. Baldevia,Jr, (2000) Guam Power Authority Under Frequency Load Shedding Study.

[13] William Amuna, Bernard Modey, Felix Abotsi, Moses Dowuona, Volta River Authority, (2002) Harmonized Automatic Frequency Load Shedding.

[14] ERCOT, Underfrequency Load Shedding 2006 Assessment and Review.

[15] Haibo You, Vijay Vittal, Juhwan Jung, Chen-Ching Liu, Massoud Amin, Rambabu Adapa,(2002) An Intelligent Adaptive Load Shedding Scheme, 14th PSCC, Sevilla, Session 17, Paper 6.

[16] Emmanuel J. Thalassinakis, Evangelos N. Dialynas, Demosthenes Agoris, (2006) Method Combining ANNs and Monte Carlo Simulation for the Selection of the Load Shedding Protection Strategies in Autonomous Power Systems, IEEE Transactions on Power Systems, Vol. 21, No. 4.

[17] Ying Lu, Wen-Shiow Kao, Associate Member, IEEE, Yung-Tien Chen, (2005) Study of Applying Load Shedding Scheme With Dynamic D-Factor Values of Various Dynamic Load Models to Taiwan Power System, IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 20, NO. 4.

[18] Leehter Yao, Senior Member, IEEE, Wen-Chi Chang, and Rong-Liang Yen, (2005) An Iterative Deepening Genetic Algorithm for Scheduling of Direct Load Control, IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 20, NO. 3.

[19] Farrokh Shokooh, J J Dai, Shervin Shokooh, Jacques Tastet, Hugo Castro, Tanuj Khandelwal, Gary Donner, An Intelligent Load Shedding (ILS) System Application in a Large Industrial Facility.

[20] Oscar E. Moya, (2005) A Spinning Reserve, Load Shedding, and Economic Dispatch Solution by Bender's Decomposition, IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 20, NO. 1.

[21] Vladimir V. Terzija, (2006) Adaptive Underfrequency Load Shedding Based on the Magnitude of the Disturbance Estimation, IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 21, NO. 3.

[22] Emmanuel J. Thalassinakis, Member, IEEE, and Evangelos N. Dialynas,(2004) A Monte-Carlo Simulation Method for Setting the Underfrequency Load Shedding Relays and Selecting the Spinning Reserve Policy in Autonomous Power Systems, IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 19, NO. 4.

[23] Farrokh Shokooh, Shervin Shokooh, Jacques Tastet, Hugo Castro, Tanuj Khandelwal, Gary Donner, An Intelligent Load Shedding System Application in a Large Industrial Facility.

[24] Wen-Jen Lee, Microcomputers based intelligent load shedding.

[25] Denis Lee Hau Aik, Member, IEEE, (2006) A General-Order System Frequency Response Model Incorporating Load Shedding: Analytic Modeling and Applications, IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 21, NO.2.

[26] Rung-Fang Chang, Chan-Nan Lu, Tsun-Yu Hsiao, (2005) Prediction of Frequency Response After Generator Outage Using Regression Tree, IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 20, NO. 4.

[27] Adly. A. Girgis, William Peterson, Optimal estimation of frequency deviation and its rate of change for load shedding.

[28] Adly.A.Girgis, Shruti Mathure, Dissertation on Load shedding using voltage, frequency and their rate of change.

[29] Adly.A.Girgis, Ding Xu, Optimal Load shedding strategies in power systems with distributed generation.

[30] Li Zhang, Jin Zhong, UFLS Design by using f and integrating df/dt.

[31] Xiaofu Xiong, Wenyuan Li, A New under frequency load shedding scheme considering load frequency characteristics.

[32] H. Seyedi, M. Sanaye-Pasand, M.R. Dadashzadeh, Design and Simulation of an adaptive Load Shedding Algorithm using a real network.

[33] Matthew A. Mitchell, J.A. PeGas Lopes, J.N. Fidalgo James D. McCalley,

33.1) Using a Neural Network to Predict the Dynamic Frequency Response of a Power

33.2) System to an Under-Frequency Load Shedding Scenario.

[34] M. Parniani, A. Nasri, SCADA based under frequency load shedding integrated with rate of frequency decline.

[35] Juhwan Jung, Chen-Ching Liu, Steven Tanimoto, Vijay Vittal, Adaptation in Load Shedding under vulnerable operating conditions.

[36] B. Isaias Lima Lopes, A.C. Zambroni de Sow, (2003) An Approach for Under Voltage Load Shedding, IEEE Bologna PowerTech Conference.

[37] Dai Jianfeng, Zhou Shuangxi, Lu Zongxiang, A New Risk Indices Based Under Voltage Load Shedding Scheme.

[38] T. Amraee, B. Mozafari, A.M. Ranjbar, An Improved Model for Optimal Under Voltage Load Shedding: Particle Swarm Approach.

[39] Shamir S. Ladhani, William Rosehart, Criteria for Load Control when Considering Static Stability Limits.

[40] Naoto Yorino, E. E. El-Araby, Hiroshi Sasaki, Shigemi Harada, A New Formulation for FACTS Allocation for Security Enhancement Against Voltage Collapse.

[41] Charles J. Mozina (Beckwith Electric Co., Inc.), Undervoltage Load Shedding.

[42] CD Vournas, GA Manos, J Kabouris, G Christoforidis, On-line voltage security assessment of the Hellenic interconnected system.

[43] Mark Adamiak, William Premerlani, Dr. Bogdan Kasztenny, Synchrophasors: Definition, Measurement, and Application.

[44] Yanfeng Gong, Noel Schulz, Armando Guzmán, Synchrophasor-Based Real-Time Voltage Stability Index.